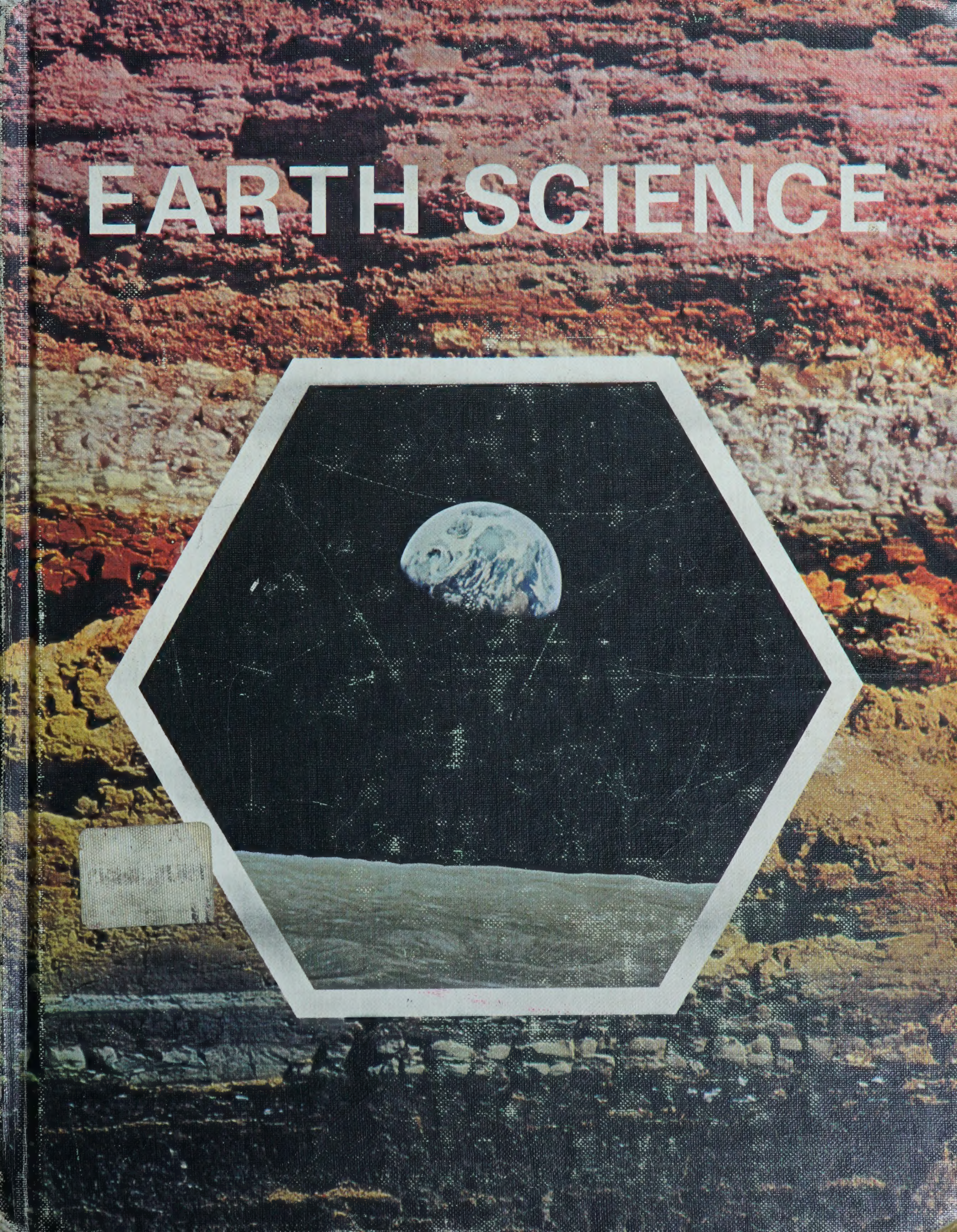
EARTH SCIENCE



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EARTH SCIENCE

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EARTH SCIENCE

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ACKNOWLEDGMENTS

Special thanks are given to the following earth scientists, who read the manuscript or parts thereof and provided detailed comments on its accuracy.

Dr. Kirtley F. Mather
Professor of Geology, Emeritus
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Dr. Jerome Spar
Professor of Meteorology
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PREFACE

During the International Geophysical Year, 1957–1958, nations cooperated with each other in studying the earth. In the same year, earth-circling satellites were first orbited. This year of study of the earth and its environment opened new horizons and started the present great interest in all the sciences. Understanding all aspects of the earth has become increasingly urgent as this planet becomes more and more populated. Man is the only species that has the ability to control his environment for good or for bad.

The problems of overpopulating the earth bring with them an awareness of the need for extremely careful use of the earth's resources. In order to develop this awareness, we must learn all we can about the earth. People who have acquired some knowledge of the earth will be better able to discuss and determine issues that involve water and mineral (and perhaps even air) conservation, water and air pollution, weather control, offshore drilling for oil, the peaceful use of atomic devices, and even the exploration of space.

The new ideas and techniques injected into science teaching by government-sponsored programs are most welcome. However, the texts that were written by large committees are excellent for only a small portion of the school population —those young people who already desire to become scientists. We believe there should be earth science texts for all students. An earth science course for young people should be like a course in literature. It should form a lasting understanding and appreciation of what one will be surrounded with for the rest of his life —instead of books, the earth with its varied features, forces, and processes.

We believe students must start with a background of observable and immediately understandable phenomena of the earth. Then they can understand the abstract theories concerning space, the interior of the earth, fields and forces, and even the rock cycle. Man's earliest concepts were usually those that are most obvious and that are supported by direct observation. Therefore we believe the easiest way to comprehend an area of knowledge is to follow the historical sequence of development of the accepted concepts. For this reason the text moves from *what we see happening*, to *what we believe is happening*, and finally to *what we are exploring*.

It has been conventional to break up earth science into a study of the lithosphere, the hydrosphere, the atmosphere, and space. When that is done, the student does not get a true understanding of the earth as a whole. There is such an interplay among the three spheres of the earth that one sphere cannot be understood without some knowledge of the others.

To overcome this artificial separation into spheres, we have done considerable interweaving. Therefore the text is not strictly divided into units of geology, oceanography, meteorology, and space. However, there are such areas as the development of earth science, the history of the earth, water on the land, water in the ocean, to list a few. All these topics have been introduced according to the logic of the presentation, and one chapter flows naturally into the next.

Pronunciation Guide

The pronunciations used in this text are based on *Webster's Third New International Dictionary.* The phonetic symbols that are used are those shown in the key below. Primary accents are indicated by small capital letters; for example, geology (jee OL uh jee).

Symbol	Sound	Symbol	Sound
a	h*a*t	oo	c*oo*l
ah	f*a*ther	oy	f*oi*l
air	h*air*	ow	cl*ou*d
aw	*Au*gust	u, uh	sod*a*
ay	l*a*dy	ur	lett*er*
e, eh	s*e*t	g	*g*et
ear	h*ear*	j	*J*une
ee	*ea*sy	k	*c*ape
i, ih	b*i*ll	kh	a*ch* (German)
y, ye, eye	m*i*nd	z	boy*s*
o	d*o*t	zh	mea*s*ure
oh	*loa*n		

CONTENTS

CHAPTER 1

DOWN TO EARTH

Most of us are interested in the scientific discoveries of the past. We also want to know something about the people who made them. Everything we know originated in some person's mind. The reason we know of a person's discovery is that he was able to communicate his new idea to other people. Thus, new ideas are passed on from one generation to the next because man has learned to communicate. We are going to try to pass on to you some of the discoveries about the earth that were made by the many generations of men and women who have preceded you.

1-1 EARTH SCIENCE

What we know about the earth can be divided into three closely related sciences: **geology**, the study of the solid earth; **oceanography**, the study of the oceans; and **meteorology**, the study of the atmosphere that surrounds the earth. Since the earth is a member of the universe, its study is also part of another science—**astronomy**. After we have discussed the earth, we shall see where it fits into the universe.

As we learn more and more about each of the three branches of earth science, it becomes evident that none of them can be fully understood without knowledge of the others. For example, the water that shapes the mountains and plains by wearing them away comes directly from clouds in the atmosphere. Much of the water vapor that forms clouds comes from the oceans. Thus, the common occurrence of rain is an event that involves three branches of earth science. This being so, it is best to start studying earth science as one subject and not as three or four different subjects.

The constant interplay among the forces of the ocean, the atmosphere, and the land causes an ever-changing earth.

Figure 1-1 The presence of water on and around the earth or any planet determines the appearance of that planet. Since water is in the air, on the land, and in the ocean, it is the unifying factor of the earth sciences.

1-2 THE EARTH SCIENTISTS

There are various reasons for studying the sciences of the earth. A few people study these subjects because they intend to make one of them their lifework. Such specialists in earth science are geologists, oceanographers, and meteorologists. Of the three, the greatest number are geologists. Geology is the oldest branch of earth science and the one about which we know most. The knowledge geologists have gained has come from studying the relatively thin outermost part of the earth, called the **crust**.

A large part of geology is based on *direct* observation of this very thin upper layer of the earth. Our knowledge about the rest of the 6,400 kilometers (4,000 miles) down to the center of the earth is based on *indirect* observations and on a series of good guesses.

What geologists know about the upper part of the crust of the earth is very useful to us. The materials from which our huge buildings are constructed are products of the crust of the earth. The metal in the printing press used to print this book came from the earth. The highways that cross the land, and the bridges and tunnels that carry traffic from one side of a river to the other could not have been built without the aid of earth scientists.

Figure 1-2 From this airplane of the United States Weather Bureau, scientists studied the characteristics of a swirling hurricane.

Meteorologists, scientists who study the atmosphere, also make important contributions. It is through their knowledge of what happens to air as it heats or cools that predictions can be made about the weather. Not very many years ago, hurricanes struck with little or no warning. No one had time to protect himself or his property against the force of the howling winds. Today meteorologists can give us warning days in advance of an approaching hurricane.

In time, the statement, "Everybody talks about the weather but nobody does anything about it," may no longer be true. At present there is nothing we can do to prevent hurricanes. Experiments now under way may teach us how we can turn a hurricane from its path and direct it into an area where little damage will be done. Meteorologists have tried to make rain fall when and where it is needed. So far, they have not been very successful.

For more than two thousand years, men have sailed upon the surface of the oceans, with little or no knowledge of the depths beneath them. Even today we know probably as much about the surface of the moon as we do about the bottom of the oceans. What oceanographers have learned has given us a much better understanding of the relationship between the earth's water and the land and atmosphere.

Very slowly we are learning how to use the knowledge being gained by oceanographers. We are benefiting from their discoveries about food chains in the oceans. New food products obtained from the sea are being used to feed people in underdeveloped nations. Before long we may be recovering valuable minerals from the floor of the oceans. Oceanography offers an interesting future for those of you who like the sea and are willing to do the hard studying necessary to become a scientist.

Figure 1-3 Life at sea for an oceanographer can be rough, wet, and cold. Earth scientists must often forgo the comforts of home to pursue their studies.

Figure 1-4 Underwater research by geologists has indicated the existence of oil under the ocean bottom. Here a helicopter prepares to land on an offshore drilling rig in the Persian Gulf.

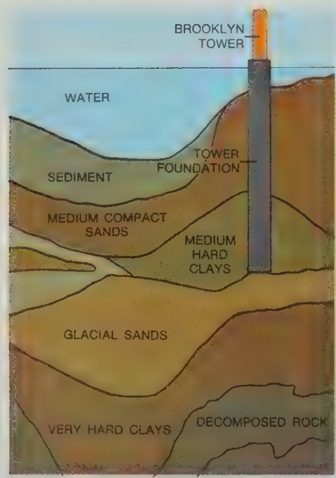


Figure 1-5 A knowledge of geology is necessary to determine the composition of underlying rock before a bridge can be built. The towers must rest on material strong enough to bear their weight.

1-3 EARTH SCIENCE AND YOU

A few individuals study the earth sciences to become specialists in those subjects, but what about the others? Why should you learn something about earth science? Many of you may someday need the advice of an earth scientist. Therefore, you should know the kinds of things earth scientists study and the kind of advice they can give you.

Companies engaged in mining or drilling need the advice of geologists if they are to be successful. Perhaps less widely known is the importance of geologists to construction companies. Very often the safety of a large building, a bridge, a tunnel, or a highway depends on the judgment of a geologist.

In April 1962 a mild earthquake shook the city of Denver. No one paid much attention to it. The next month, there were fourteen or fifteen similar quakes. Geologists were puzzled, because Denver is situated in a region where earthquakes had not occurred so frequently in the past. During the next three years, there were hundreds of these mild earthquakes. Geologists found that these shocks originated in a relatively small area northeast of the city.

Investigation showed that one month before the April 1962 earthquake, workers at the Rocky Mountain Arsenal had

changed the way they disposed of contaminated water. They had begun pumping it down a well drilled to about 4,000 meters (13,000 feet) below the surface. The amounts of water pumped into the well in succeeding months were compared with the frequency of the earthquakes. It appeared conclusive that there was a relationship between them.

David M. Evans, a geologist, had an explanation for this problem. Earthquakes are caused by rocks slipping over one another. In the Denver area, stresses that could lead to destructive earthquakes may be building up in the rocks. Evans suggested that the water was acting as a lubricant, allowing the rocks to slip more easily. This slowly released the stress that could have been destructive. In the future, we may be able to protect cities in natural earthquake areas by relieving the stress in rocks slowly. Instead of there being one large, city-destroying earthquake, there may be many small, nondestructive earthquakes spread over several years.

Another reason for studying earth science is that we get pleasure from knowing something. All of us are curious about our surroundings. Through the study of earth science, we learn a little about how the seashore, the plains, and the mountains developed. We begin to appreciate more fully the scenery that surrounds us, no matter where we are or where we go.

One of the things we often do not realize is how completely we depend on the earth to supply everything we need. Food, clothing, housing, and the materials and tools we use to earn a living all have their origin in the earth. The sun supplies energy to the earth, and the interaction of matter and energy makes life possible. When an astronaut leaves the surface of the earth, he must carry from the earth everything he needs to support life—food, water, oxygen.

Figure 1-6 An astronaut performing extra-vehicular work must wear a specially designed space suit. These space suits are attached to the life-support systems and carry emergency equipment.

1-4 EARTH SCIENCE AND THE OTHER SCIENCES

The earth sciences are strongly dependent on physics and chemistry. To help solve problems about the earth, the earth scientist uses what physicists and chemists have learned. He should also know something about plants and animals. Their remains, buried in rocks as fossils, are important clues to the theory of the evolution of life on earth. In short, earth scientists use the other sciences as tools with which to investigate the earth.

Some scientists have combined a knowledge of two sciences, so we have had to invent special names for these

paleontologist (pay lee on TOL uh jist); Greek: *palai*, long ago + *onta*, existing things + *logos*, reason.

men. Some of these names are easily understood. For example, since *geo-* is the prefix that means "earth," a **geophysicist** is an earth physicist.

A few of the names are not so obvious in meaning. A person who studies fossils combines a knowledge of biology and geology. He is called a **paleontologist**.

1-5 THE EARTH IS A LABORATORY

We often think of a scientist as spending most of his time performing experiments in the laboratory. This is only partly true. All scientists use the laboratory for gathering certain kinds of facts and for testing ideas. Practically all the research carried out by physicists and chemists, and much of that done by modern biologists, is performed in the laboratory. This cannot be said about the research of many earth scientists.

Earth scientists use laboratory studies and research to help solve problems, but many of their problems cannot be solved in the laboratory. There are two good reasons for this. First, many of the things that earth scientists study cannot be brought into the laboratory (see Figure 1-8). A volcano, a hurricane, or an ocean wave must be studied where they are. Therefore, the entire world is the outdoor laboratory of earth scientists.

Figure 1-7 This paleontologist is removing the fossilized remains of a dinosaur found in Utah. A knowledge of biology and geology is essential in his work.

Figure 1-8 The temperature of lava is measured by an instrument called an optical pyrometer. Notice the asbestos suit worn by a scientist descending into an active crater.

Most actions and changes that earth scientists study occur very slowly—another reason why working in a laboratory is often impossible for earth scientists. In our daily lives a year is a long time. If an experiment is planned that will take a year to accomplish, we think carefully before starting it. Very few of the things that earth scientists want to test take place in so short a time. Therefore, earth scientists must solve many of their problems in other ways.

Suppose the problem is "How does a mountain form?" The way an earth scientist attacks such a problem is to visit and study a great many mountains. He learns a little from each of the mountains he studies. When he believes he has studied enough mountains, he puts together all the bits of information he has gained. Then he tries to make a general statement of what he has learned about all mountains.

There is no way to prove that his explanation of how mountains form is the correct one. But suppose another scientist, studying other mountains, finds that his explanation also fits the mountains first studied. We can then *assume* the original explanation may be a correct one. Remember, in spite of all this study, nothing has been *proved* about how

mountains are formed. All we have is an idea about how they may have been formed. This kind of untested idea is called a **hypothesis**. You will find that there are a great many hypotheses in earth science.

Figure 1-9 Chemists construct models of the way elements such as sodium and chlorine combine to form a mineral.

1-6 THE IMPORTANCE OF WORDS

A set of words having very precise meanings is one of the characteristics of every science. We use some of these same words in everyday conversation, but without the same precision.

Consider the two words *rock* and *stone*. When we use these words in ordinary conversation, they are frequently interchanged. When an earth scientist uses these words, they have very precise meanings and cannot be interchanged. For earth scientists, the word *rock* means a specific kind of substance. There are hundreds of different kinds of rocks that are recognized by geologists. A fragment of any one of them is a *stone*.

A **rock** is a substance with a characteristic mineral composition. A **mineral** is a substance that is a unique combination of chemical elements arranged in a specific pattern.

Common table salt is an example of a mineral. Chemically, it is composed of equal numbers of atoms of two elements, sodium and chlorine, as shown in Figure 1-9. Billions of these groups of atoms are found in one tiny cubic crystal of **halite,** which is the mineral name for table salt. One of these crystals can be seen under a hand lens (see Figure 1-10).

Figure 1-10 Crystals of common table salt have the appearance of cubes. Each cube contains billions of atoms.

Figure 1-11 Granite is a rock composed of two or more minerals. The appearance of granite varies, depending on the kind and the amount of minerals it contains.

Look at Figure 1-11. **Granite** is one of the most common types of rocks. There are many varieties of granite, but all contain the minerals quartz, feldspar, and mica also shown in the picture. The name *granite* is applied to a whole family of rocks.

In the laboratory or in the field, you can learn how to recognize the important rock-forming minerals individually or as they are found jumbled together in a rock. Appendix I shows you something about how to recognize common minerals. Appendix II teaches you how to recognize some common kinds of rocks. You do not need to know a great deal about rocks and minerals to understand earth science, but some knowledge of them is fundamental. Besides, it is fun to be able to name the rocks and minerals you find outdoors.

1-7 MEASUREMENTS

Throughout history, man has devised many systems to measure his world. Today two systems are in general use. In the United States and Canada, the **English system** is used. This system is based on units such as the foot, pound, and quart.

In 1960 International System of Units was adopted as the official name of the metric system at a meeting of scientists from 36 nations.

The metric system, now called the **International System of Units**, is used in all other countries. It is based on units such as the meter, gram, and liter. Whatever their nationality, most scientists use the international system for their work. Most of you, however, are more familiar with the English system.

In this book, we use both systems, with emphasis on the international system. For certain measurements that scientists make, such as density, the international system is always used. In cases like this, we will use this system. When the measurement can be made in either system, we may give both measurements. Table 1-1 shows how to convert measurements of the English system into their international equivalents, and vice versa. As you can see from the table, any unit in the international system is larger or smaller than the next by a power of 10. Look at the difference between a meter and a centimeter, and a meter and a kilometer.

Table 1-1 Equivalents within the international system

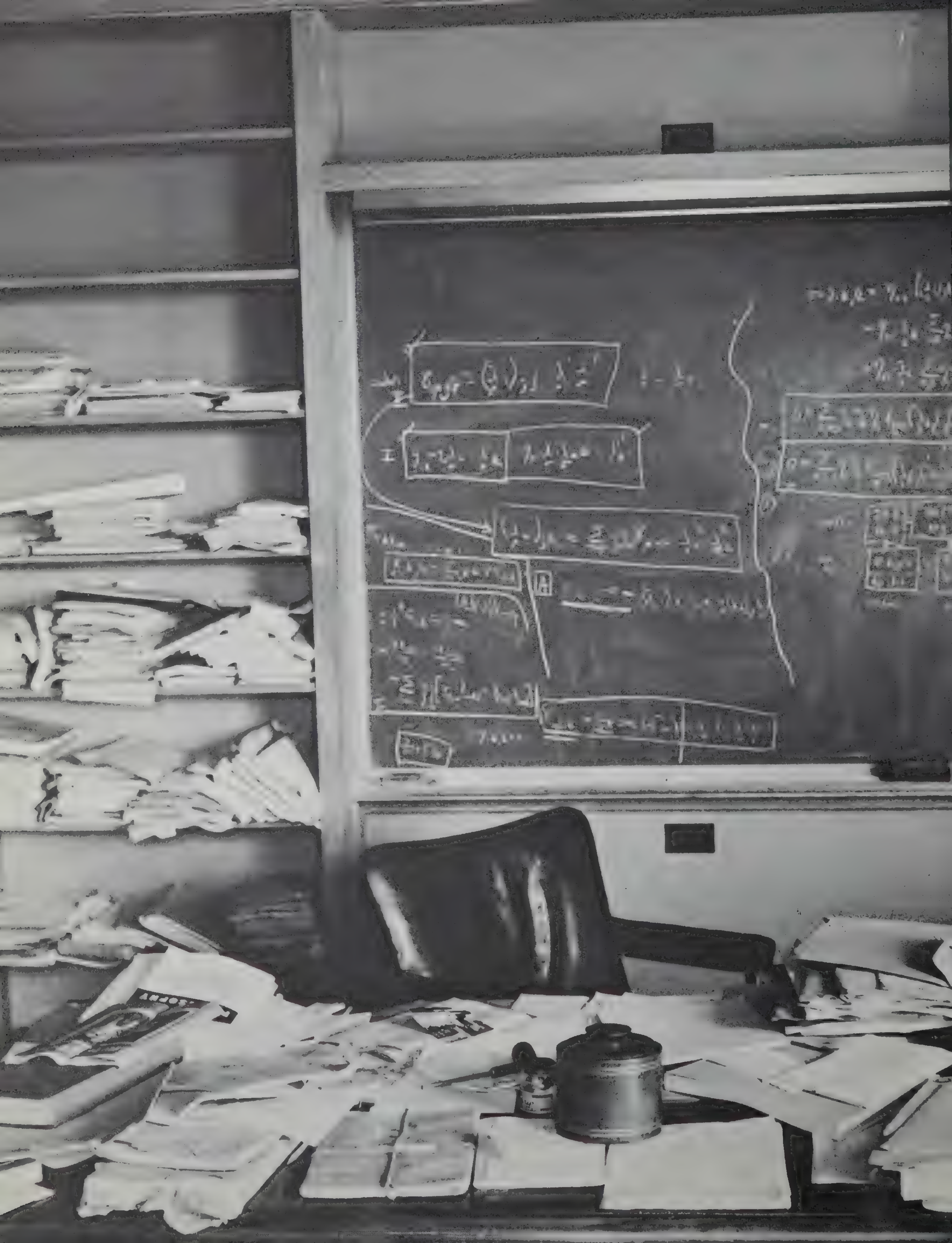
Units of length	
1 centimeter	10 millimeters
1 meter	100 centimeters
1 kilometer	1,000 meters
Units of volume	
1 liter	1,000 milliliters
1 milliliter	1 cubic centimeter
Units of mass	
1 gram	1,000 milligrams
1 kilogram	1,000 grams
Units of conversion	
English system	*International system*
0.39 inch	1.0 centimeter
1.0 inch	2.54 centimeters
39.37 inches	1.0 meter
0.62 mile	1.0 kilometer
1.0 mile	1.6 kilometers
1.0 quart	0.94 liter
1.06 quarts	1.0 liter
1.0 pound	454.0 grams
1.0 pound	0.45 kilogram
2.2 pounds	1.0 kilogram

Temperature can also be measured in two ways, in degrees Fahrenheit (°F) or in degrees Celsius (°C). Scientists usually use the Celsius scale. When necessary, the equivalent in degrees Fahrenheit will appear in parentheses. Section 10-4 shows how to convert from the Celsius scale to the Fahrenheit scale, and vice versa.

Celsius (SEL see us) is a scale often called the centigrade scale because there are 100 degrees between the freezing and boiling points of water.

SUMMARY

Earth science is the study of the solid earth, the water on it, and the atmosphere surrounding it. The study of the solid earth is geology, the study of the oceans is oceanography, and the study of the atmosphere is meteorology. All three must be combined in order to completely understand the earth. The knowledge gathered by earth scientists has helped make our nation wealthy and our civilization advanced. A general understanding of earth science can help us live fuller and happier lives and can often help us in our vocations. Earth science, like other sciences, teaches us the need for precision in what we do and in what we say or write. Earth science provides a unique study of how hypotheses that cannot be tested in the laboratory are developed.



CHAPTER 2

TWO LAWS OF SCIENCE

To many people the word *scientist* implies a very serious person wearing a long white coat and surrounded by curiously shaped glassware. There are some scientists who do work wearing a protective coat in a laboratory filled with apparatus. There are others who need no special uniform and who do their best scientific work in a quiet room filled with books. Still others you will find in rough clothes, doing their work outdoors, often far from cities and towns. Earth scientists can fit any of these descriptions. All of them are seeking to learn more about the physical universe that surrounds us.

2-1 SCIENTISTS AT WORK

Scientists learn by making observations, studying them, and drawing general conclusions. This is not very different from the way historians, economists, and businessmen work. One aim of scientists is to learn enough about matter and energy to be able to predict what will happen when certain events occur in nature.

Once scientists have studied a phenomenon thoroughly and think they fully understand it, they try to state a rule about it. The rules of science are usually called **laws**. Because a scientific law is based on measurements, we can usually express it as a mathematical equation. Before this can be done, the idea embodied in the law must be thoroughly tested. Sometimes this testing of the idea, called **experimentation**, can be done in the laboratory. Sometimes it cannot. If not, experimentation can be done only by making many more observations of the phenomenon in nature.

Ideas do not always lead directly to scientific laws. Usually a new idea proves to be only partly right or even all wrong. While an idea that seems to be right is being studied and

In his laboratory, Einstein attempted to interpret the facts of energy and matter in a logical and orderly way.

Figure 2-1 Isaac Newton (English, 1642–1727). Newton's discoveries are the basis for modern physical science. He is probably best known for his quantitive study of motion and the invention of calculus.

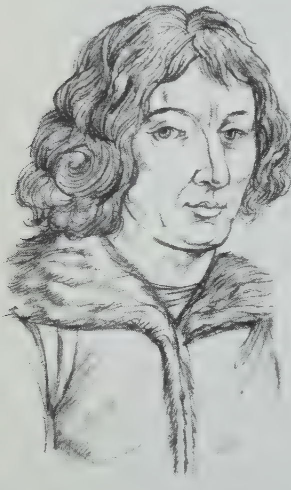


Figure 2-2 Nicolaus Copernicus (Polish, 1473–1543). The first real challenge to Ptolemy's theory of the universe was put forth by Copernicus. His theory of a heliocentric solar system is the basis for modern developments in planetary astronomy.

tested, it is called a hypothesis. A hypothesis that many experimenters agree may be correct is called a **theory**. Tested and proven theories are called laws.

In this chapter we shall examine the development of two great laws of science—the law of gravitation and the law of conservation. Both affect all branches of science and are important in earth science. There are some scientists who believe these are the only fundamental laws in the universe.

The man most responsible for the law of gravitation was Sir Isaac Newton, an Englishman. Newton, of course, did not invent gravity. He found a way to explain it. Gravity existed long before there was an earth. To understand why Newton became interested in gravity, we must first study what another scientist had discovered some years before Newton was born.

2-2 KEPLER'S CONTRIBUTION

At the beginning of the sixteenth century, Nicolaus Copernicus, a Polish astronomer (see Figure 2-2, came to the conclusion that all the planets, including the earth, revolve around the sun in circles. Nearly a century later, the German astronomer Johannes Kepler set about calculating the orbit of Mars, the planet that lies just beyond the earth in the solar system. For this task he had hundreds of careful observations made by his teacher Tycho Brahe, a Danish astronomer, and a great many that he had made himself.

When Kepler used Brahe's data to predict where Mars would be at a particular time, he found that his prediction was wrong. Kepler was sure Brahe had not made an error. After trying several ways of explaining the problem, Kepler discovered that it was Copernicus who had been mistaken. Mars and the other planets do not travel in circles around the sun but in orbits shaped like an ellipse (see Figure 2-4). This statement is known as **Kepler's first law of planetary motion**.

The second fact Kepler discovered is that Mars's velocity along its orbit changes. Mars has a higher velocity when it is closer to the sun than when it is farther away. Kepler concluded that his observations could be stated in a simple mathematical way: In any unit of time, the *area* swept by an imaginary line joining the sun to Mars is *constant*, regardless of whether Mars is moving slower or faster than average. In Figure 2-5 the elliptical shape of the orbit of Mars has been exaggerated to make things clearer. It is more like a circle.

Other astronomers applied Kepler's idea to other planets and to the earth-moon pair. In each case, they found Kepler's idea to be true. It is now called **Kepler's second law of planetary motion**. The artificial satellites that are put into orbit around the earth perform in accordance with Kepler's laws. They travel faster when near the earth and slower when more distant.

Figure 2-3 Johannes Kepler (German, 1571–1630). His theory of the motion of the planets is the foundation of modern dynamic astronomy. Kepler was actually a court astrologer, whose task it was to make predictions from the stars.

Study Guide

1. What is the aim of scientists?
2. What is a hypothesis?
3. State what Copernicus believed about the movement of the planets.
4. On a piece of paper, diagram Kepler's second law of planetary motion.

2-3 WHAT NEWTON DECIDED

Nearly a century after Kepler had published his findings about the orbit of Mars, Newton began to wonder why the planets behave as they do. Kepler's ideas about Mars had been confirmed by other astronomers. They had also found that all the planets behave just as Mars does. Newton reasoned that an object in space should move in a straight line unless something interferes with it. He was convinced that something interferes with the planets, because their orbits are elliptical.

Newton had already derived several ideas about the motion of bodies in space and on the earth. One of these ideas was that in order to change the speed or direction (the acceleration) of a moving object (a mass), a force must be applied to it.

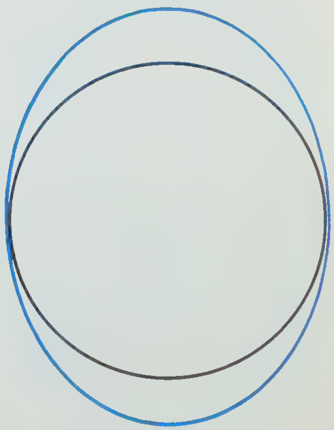


Figure 2-4 The "out-of-roundness" of the elliptical orbits of the planets is much less than in the ellipse shown here.

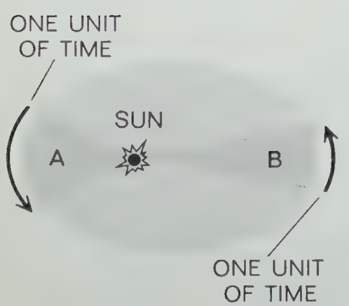


Figure 2-5 Area A is swept out by the line from the sun to Mars in one unit of time when Mars is closest to the sun and traveling most rapidly in its orbit. In the same length of time, area B is swept out by the line when Mars is most distant from the sun and traveling most slowly in its orbit. The two areas, A and B, are equal.

Mass is the property that allows a body to have weight in a gravitational field. All matter has mass and the larger the amount of matter, the larger the mass. Mass is always measured in international units.

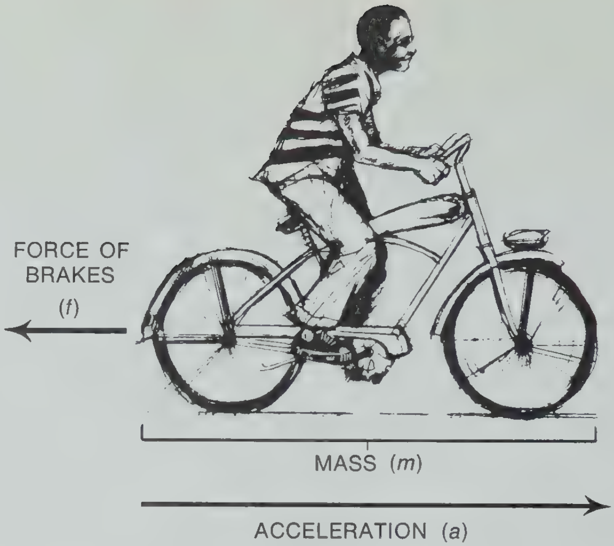


Figure 2-6 Acceleration can be either the speeding up or the slowing down of a mass. A force must be applied to the handlebars to change the direction in which the bicycle is going. This is also an acceleration.

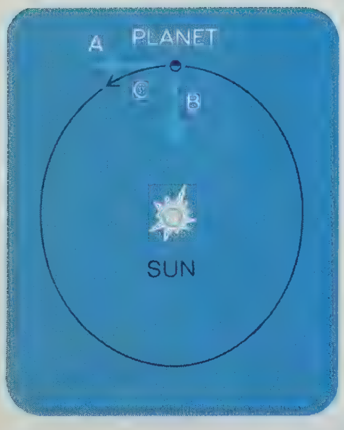


Figure 2-7 The force that keeps the planets in orbit is coming from the sun.

A simple example of this idea is the use of the brake to stop a bicycle. In Figure 2-6 the force, f, represents the friction of the brake on the wheel. The acceleration, a, is the slowing down of the bicycle, the mass m. The amount of force necessary to stop the bicycle is equal to the product of the mass and the acceleration. This can be written as a mathematical equation:

$$f = ma$$

With these ideas as a basis, Newton reasoned that there must be a force that keeps the planets revolving around the sun. This force and the tendency of the planets to fly off in a straight line combine to make the planets follow an elliptical orbit. Look at Figure 2-7 and you will see how the force works.

In 1687 Newton's idea about this force was heard for the first time. The force was called **gravity**, and Newton reasoned that every piece of matter in the universe exerts this pulling force on every other piece. Newton's theory of gravitational attraction became known as the **law of gravitation**. The amount of the force depends on the amount of matter (the mass) and the distance between the masses. This can also be

written as a mathematical equation, using the following symbols: f is the force of gravity; m_1 is one of the masses (say the sun); m_2 is the other mass (th planet Mars); and r is the distance between them. The equation is written:

$$f = \frac{m_1 m_2}{r^2}$$

Using Newton's two equations, we can explain the idea that Kepler first stated—that a planet will move faster as it gets closer to the sun and slower as it gets farther away. Let the force, f, in both equations be equal to the gravitational attraction between Mars and the sun. The masses, m_1 and m_2, can be those of Mars and the sun. They never change. The acceleration, a, is the change in the speed at which Mars moves through space at any moment. As Mars gets closer to the sun, the distance, r, between them gets smaller. In Newton's equation for gravity, if r becomes smaller, what happens to f? It gets larger. We say that f is in **inverse proportion** to r. So as Mars gets closer to the sun, the gravitational attraction, f, between them gets larger.

Now put this new, larger value of f into Newton's first equation. If f gets larger, what must happen to the acceleration, a? Remember, mass, m, does not change. You should be able to see that a will increase. We say that a is in **direct proportion** to f. Therefore, as a planet gets closer to the sun, the sun's gravitational attraction for the planet will increase, and the planet's speed will increase. In the same way, as Mars gets farther away from the sun, its speed will decrease. The work of astronomers since Kepler has shown that these laws hold true for all objects that revolve around the sun. Today the same principles are used in planning the orbits of space vehicles.

Figure 2-8 The only reason the object travels in a circle around the boy's head is that he is pulling on the string. The string is attached to the object and is pulling on it. If the boy lets go of the string, the object will fly off in a *straight line* away from his head.

2-4 A PECULIAR THING ABOUT GRAVITY

Although we know how to measure the force of gravity and how to use the law of gravitation, we do not know *why* there is gravity. It is easy to imitate the motion of a planet revolving around the sun. All you need to do is tie a piece of string to an object and whirl it around your head as shown in Figure 2-8. The object is the model planet, and your head is the model sun.

To keep the object in its orbit, you must pull on the string. The gravity that keeps the planets in their orbits is represented by the string. It is a force that is acting at a distance.

Gravity is peculiar in that way. Magnetism is another force that acts at a distance. Neither of these forces has been wholly explained. Their complete explanation awaits the future.

Study Guide

1. What idea made Newton believe some force interferes with the motion of the planets?
2. Why do the planets orbit around the sun?
3. Does a planet move faster, or slower, as it gets closer to the sun?
4. From your own experience, give at least one example of a direct proportion.

2-5 THE LAW OF CONSERVATION OF MASS

Several things happened late in the eighteenth and early in the nineteenth century that resulted in the other fundamental scientific law—the law of conservation. First, the metric system of measurement was invented. Second, accurate balances were invented. And third, chemistry became a true science.

Lavoisier had an instrument that Priestley lacked – an accurate balance. During his experiments with mercury, Lavoisier discovered that the weight of the mercury he used remained constant. He changed the mercury to mercuric oxide and back again several times, but the mass of the element did not change.

The first law of conservation, called the **law of conservation of mass**, was the result of work done by several scientists living in different countries (see note in margin).

The idea of conservation of mass began to develop when an English chemist, Joseph Priestley, extracted the gas oxygen from the air. He did this by heating mercury in air to form a red powder, called mercuric oxide. When he heated this powder more strongly, it decomposed back into mercury and oxygen. He journeyed to Paris to discuss this discovery with the French chemist Antoine Lavoisier. Priestley knew that Lavoisier was studying the problem of why things burn (see note in margin).

The Swedish chemist Jöns Jakob Berzelius showed by careful work that each compound has a very definite chemical composition, which does not vary. He also demonstrated that in every chemical reaction the mass of material used exactly equals the mass of material produced. This proved that in a chemical reaction, matter is neither created nor destroyed. It is this idea that lies behind the law of conservation of mass. The law states that matter cannot be created or destroyed by chemical means.

2-6 ANOTHER CONSERVATION LAW

After the law of conservation of mass was recognized, scientists began to explore the possibility that there might be a similar law about energy. The difficulty that faced these scientists was how to test the idea. There is no one quality common to all forms of energy. Each form must be measured in a different way.

During the first half of the nineteenth century, physicists explored the properties of different forms of energy—heat, light, electrical, and mechanical. They discovered that all forms of energy can be converted to heat energy. The first steps were taken in 1824 by Nicolas L. S. Carnot, a French physicist, when he determined that there is a relationship between mechanical energy and heat energy. In 1840 James Prescott Joule, an English physicist, precisely measured that relationship.

During the middle of the nineteenth century, relationships between the other forms of energy were established. James Clerk Maxwell, a Scottish physicist and mathematician, put all this information together mathematically and showed that energy, like matter, is conserved. Energy may be changed from one form to another, but in the process, none is lost and none is created. Another powerful tool was put into the hands of scientists when the **law of conservation of energy** was proved. In this case, it was done mathematically by one man, but the law was based on the experiments of many.

Figure 2-9 Antoine Henri Becquerel (French, 1852–1908). He pioneered in the study of radioactivity. In 1903 he shared the Nobel Prize in Physics with the Curies. Becquerel also conducted studies of magnetism, polarization of light, phosphorescence, and the absorption of light in crystals.

Study Guide

1. What did Berzelius demonstrate that led to the law of conservation of mass?
2. State the law of conservation of mass.
3. List some of the forms of energy.
4. Can one form of energy be converted to another form of energy?

2-7 A NEW IDEA IS BORN

In 1896 a prominent British physicist stated that he believed all the important principles of physics had been discovered. In the autumn of that year, Antoine Henri Becquerel, a French physicist, announced the discovery of radioactivity (see Figure 2-9 and Section 8-4). This was a new and totally unexpected physical phenomenon. The story of what developed from this discovery is the history of modern physics and mathematics.

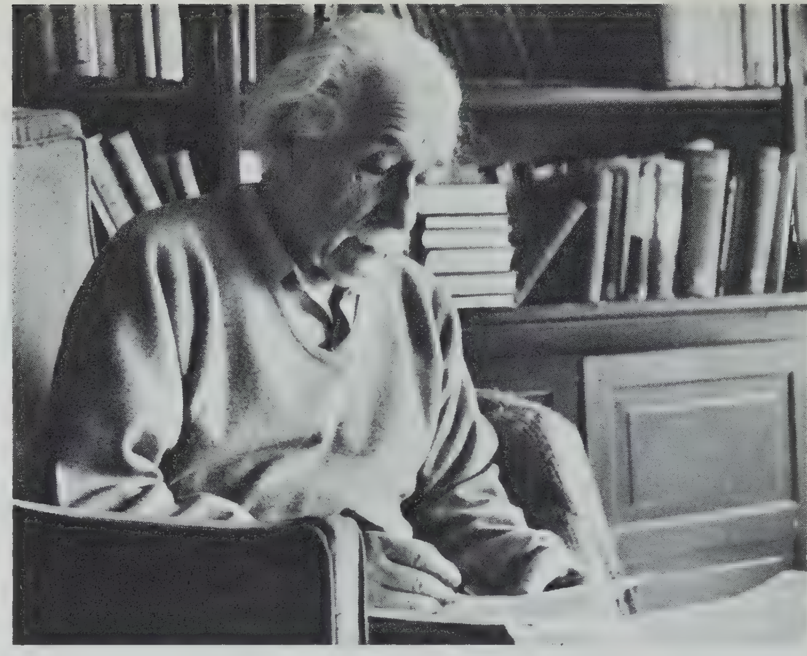


Figure 2-10 Albert Einstein (German-American, 1879–1955). Awarded the Nobel Prize in Physics in 1921 for his photoelectric law, Einstein became the leading force in modern physics. He is best known for his special and general theories of relativity.

One of the mathematicians who became interested in radioactivity was Albert Einstein (see Figure 2-10). Although born in Germany, he later became a citizen of the United States. Einstein conceived the idea that radioactivity results in matter being converted into energy. If true, this meant that the two laws of conservation were not true.

Neither Newton nor Einstein were concerned with the units involved. They were interested in the relationships the equations expressed.

Einstein expressed his belief in mathematical terms with his famous equation $e = mc^2$. The symbol e stands for energy, m for mass, and c for a very large number. Notice that this is the same way Newton expressed his idea about gravity, without attention to the units of measurement to be used (see note in margin).

fission (FISH un).

In 1939, Einstein suggested to President Roosevelt that it might be possible to release enormous amounts of energy from the radioactive element uranium. The result of that suggestion was the creation of the first atomic bomb. In this device a small mass of uranium was changed to energy. The rapid release of this energy caused the huge explosion shown in Figure 2-11. The process of disintegrating a piece of matter to release energy is called **fission.**

During the experimental work that led to the production of the atomic bomb, several other discoveries were made. First and foremost, units for Einstein's equation were discovered.

Energy is measured in electron volts, and mass in atomic mass units; c is the speed of light in centimeters per second.

c is equal to about 3×10^{10} (30 billion) centimeters per second, or about 186,272 miles per second.

Using these units, it became possible to predict the amount of energy that would be released by the radioactive change of matter. The conversion of one gram of matter to energy releases about 2×10^{13} calories (see note in margin).

That is enough heat to melt about 49 cubic kilometers of ice, which is enough to cover the state of Rhode Island with ice 15 meters thick. If the number 2×10^{13} seems strange to you, learn about this kind of number in Appendix IV.

Scientists have recently discovered that under the right conditions 4 atoms of hydrogen can combine to form 1 atom of helium. This is called **hydrogen fusion**. Some of the mass of the original hydrogen atoms is converted to energy. For centuries, scientists have wondered about the source of energy in the sun and the other stars. A hundred years ago they learned that there were huge amounts of hydrogen and helium in the sun. Could the fusion reaction that forms helium from hydrogen be the source of the sun's energy?

fusion (FYOO zhun).

2-8 THE NEW LAW OF CONSERVATION

Both the reactions that have been studied—the disintegration of atoms (fission) and the joining of atoms to make new kinds (fusion)—result in matter changing to energy. Nineteenth-

Figure 2-11 An atomic explosion at Frenchman Flat, Nevada, shows a tremendous release of energy.

century scientists believed that matter and energy were indestructible and that neither could be created. How could the new twentieth-century knowledge be used to state a new conservation law? It was done simply by combining the two old laws. Now we believe that the total amounts of matter and energy in the universe cannot be changed but that matter and energy can change from one to the other. This is the **new law of conservation**.

Only those scientists who are working with radioactive materials need to use the new conservation law. For all other chemists and physicists, the old laws of conservation of matter and energy are still useful. When earth scientists study the source of solar energy and the energy that escapes from within the earth, the new law must be considered.

Figure 2-12 Gravimeters must be calibrated against a series of base stations so that different readings can be interpreted as gravity values. Give a reason why gravity values at sea level and on mountains might differ from base station readings.

2-9 THE TWO LAWS AND EARTH SCIENCE

Both the law of gravitation and the law of mass-energy conservation are very important to earth scientists. The movement of the earth in its orbit around the sun and the movement of the moon in its orbit around the earth are explained by the law of gravitation. Rain falling on the earth, streams flowing downhill, and rocks falling from cliffs are also explained by that law. Using a method based on the law of gravity, we have been able to "weigh" the earth.

By measuring the variations in the force of gravity at different points on the earth, we have learned about unseen rocks beneath us. We have used the law of gravitation to help us find hidden pools of oil. You will learn about other ways in which the law of gravitation has been helpful to earth scientists.

The old laws of conservation are the basis of modern chemistry and physics. The new law of conservation is helping us learn how important solar energy is to the earth. You will find this mentioned many times in this book. You will soon discover that energy of various kinds is actively causing changes at the surface of the earth. Most of this energy is easily traced to the sun.

There are other evidences of energy at work on the earth that are not yet traceable to their origins. Where does the energy come from that raises mountains? What is the source of the energy that melts rocks and causes volcanoes?

Later in the text you will find that we are constantly seeking the source of the energy that causes things to happen. Sometimes we can suggest the source of the energy; some-

times we cannot. There is still a great deal to be learned about how and why things happen on the earth. In each case energy is involved, and its origin must be found.

Study Guide

1. Who discovered radioactivity?
2. Who first stated the idea that matter is converted to energy during radioactivity?
3. What is the process called when a mass of uranium is changed to energy?
4. State the new law of conservation.

SUMMARY

The ideas of scientists, when tested and verified, become the laws of science. The development from an idea to a law takes a long time and requires the cooperation of all scientists, without regard to nationality. One of the fundamental laws of science is the law of gravitation, which was first defined by Newton almost three hundred years ago.

During the nineteenth century, scientists discovered that neither matter nor energy could be destroyed or created by ordinary chemical or physical means. In the twentieth century, scientists have found that under certain conditions—radioactivity—matter and energy can be interchanged. Today we believe that the sum of all matter and energy cannot be changed but that matter can be changed to energy and probably energy can be changed to matter. Both the law of gravitation and the laws of conservation are important to all scientists.

CHAPTER 3

DESCRIBING THE EARTH

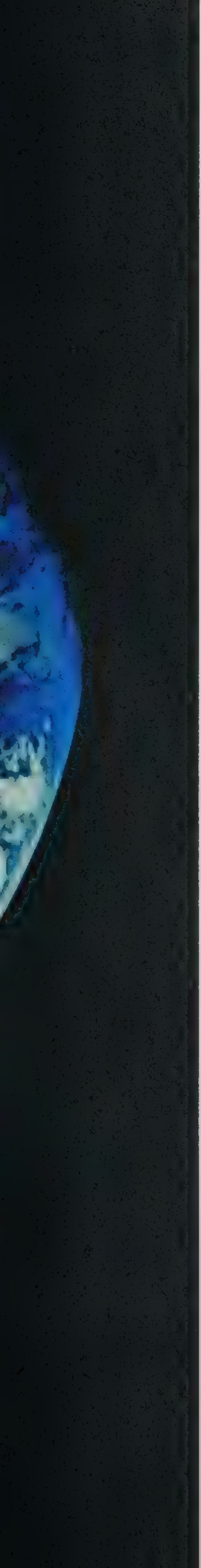
As long as 2,500 years ago, wise men in Asia, Africa, Europe, and Central America wondered about the place of the earth in the universe. These men were the forerunners of our modern astronomers. Through patient observation of the sky at night, they reached the conclusion that there were two kinds of heavenly bodies.

The first kind appear to have a fixed position, and are now called **stars**. They appear in the sky night after night and year after year in the same place *relative* to the other stars. The other heavenly bodies, which look like stars but do not have fixed positions relative to each other, are called **planets**. To remember the stars, the early students of the night sky gave names to individual bright stars. Certain groups of stars called **constellations** were also named.

3-1 A FAMILY OF HEAVENLY BODIES

An incorrect idea prevented the early observers from truly understanding the movement of the planets. They believed the earth was the center of the universe. This was natural to believe. Observers could see that the sun and the moon sailed across the sky as though they were circling the earth. Men who carefully watched the stars night after night noticed that stars, too, seemed to slowly circle the earth. Only the planets behaved differently from the rest of the heavenly bodies.

The many ideas of the ancient observers of the sky were first gathered together by Ptolemy, a Greek mathematician and scientist who lived in Alexandria, Egypt, during the second century. Ptolemy's explanation of the motion of the planets was accepted by almost everyone for about 1,300 years. His scheme is shown in Figure 3-1. To understand



The earth as seen by Apollo 8 astronauts. Note the latitudes of sparse cloud cover.

Figure 3-1 Ptolemy's scheme of the universe had the earth as the center, with the sun, moon, planets, and stars revolving in small circles around it.

Figure 3-2 The Copernican scheme of the universe was heliocentric. The sun was the center, with the earth, moon, and the planets revolving around it.

Ptolemy's explanation, and the reasons for it, we must first know something about the observations on which it was based.

The Greeks had observed the heavens for centuries. They saw the planets moving in a very regular way among the stars, except for one curious motion. Every so often, a planet, which normally moved eastward across the sky, appeared to stop for a few nights and then begin to move westward. It would continue westward for a time and then stop again for several nights and resume its eastward journey.

Ptolemy tried to explain this motion by what he called **epicycles**. He showed how a planet that revolved around a point that in turn revolved around the earth would appear to change direction occasionally (see Figure 3-1).

Three scientists played a major role in discarding Ptolemy's explanation. These were Nicolaus Copernicus, Johannes Kepler, and Isaac Newton, all of whom are mentioned in Chapter 2.

Copernicus suggested that the earth was not the center around which the heavenly bodies revolved. He stated the sun was the center (see Figure 3-2). Kepler analyzed the

motions of the planets and discovered that these could be stated in mathematical terms. Newton carried Kepler's work further and explained *why* the planets revolve around the sun as they do, and *why* the moon revolves around the earth as it does.

After the new concepts of the workings of the solar system were accepted, Ptolemy's epicycles had to be explained in another way. We now call the *apparent* change in direction of a planet's movement **retrograde motion**. Its explanation is based on the fact that each planet revolves around the sun in a different length of time – its **year**. This length of time is also called the planet's **period of revolution**. The period for Earth is 365.24 days; for Venus, it is 224.7 days; and for Mars, 687 days. During its year, Earth is passed at least once by Venus, which has a shorter trip to make because it is closer to the sun. Earth, however, passes Mars at least once a year, since Mars has a longer trip around the sun than Earth has. Earth would appear to retrograde if observed from another planet.

retrograde (REH truh grayd); Latin: *retro*, backward + *gradus*, step.

As Earth catches up to and passes Mars, Mars appears to stop in its path and begin to move backward (westward) when observed from Earth (see Figure 3-3). When Earth is far enough ahead of Mars, Mars appears to stop again and resume its normal path (eastward). Actually, of course, Mars has not changed its direction of motion.

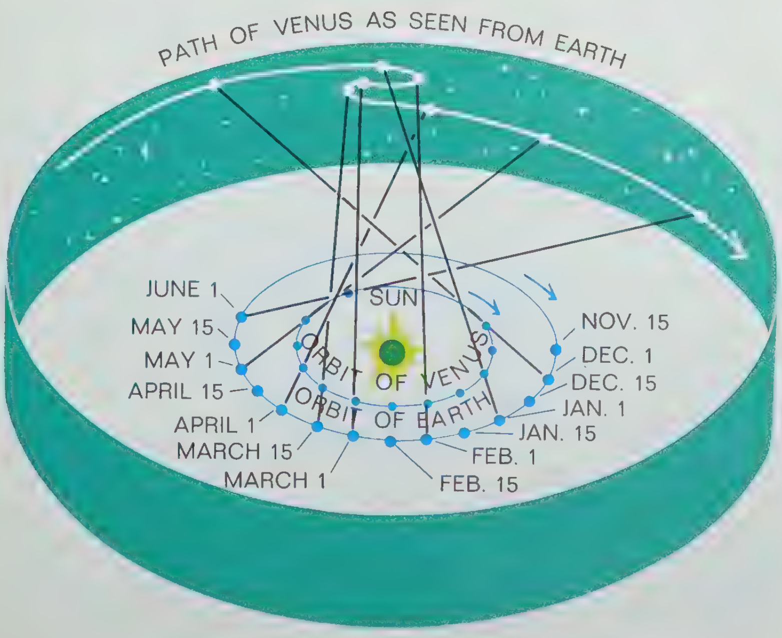


Figure 3-3 Retrograde motion is an apparent motion, just as the seeming revolution of the sun around the earth each day is an apparent motion. What happens when one car passes another? The slower car appears to be moving backward relative to the faster car.

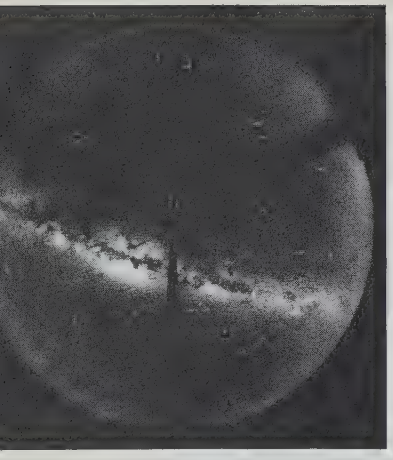


Figure 3-4 The Milky Way as seen from the Southern Hemisphere. The nucleus of the galaxy is at the center of the picture with its spiral arms extending left and right.

The studies made by astronomers over the past two hundred years have slowly brought about another change in our thinking about the importance of the earth and the sun in the universe. We no longer believe the universe revolves around the sun. We know the Milky Way is only one of at least several hundred million huge clusters of stars, called **galaxies**, that are scattered in space. Part of the Milky Way is shown in Figure 3-4. We know the sun is just a medium-sized star among the hundreds of billions that make up the Milky Way.

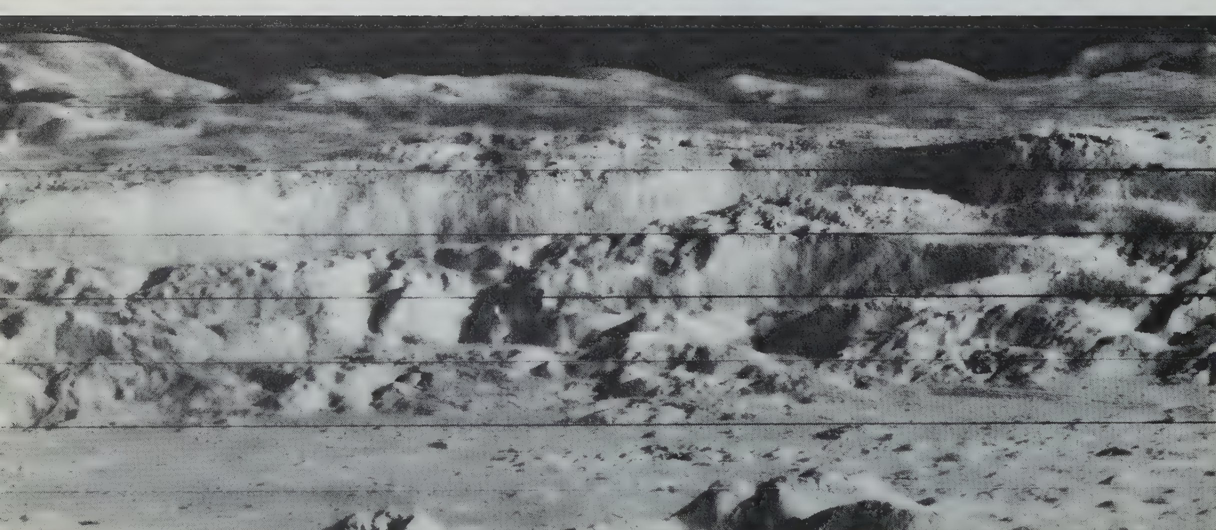
Thus, scientific investigation has demoted the earth from the center of all things to a small planet that circles a medium-sized star in the Milky Way. The sun is one of a great many stars making up one of a great many galaxies.

3-2 PROBES INTO SPACE

Now that man has begun to learn how to travel to other parts of the solar system, more and more scientists are studying the moon and the planets. Space vehicles, or probes, have taken closeup photographs of the moon and Mars.

The results of recent space probes and laboratory experiments have shown that it is highly unlikely that life as we

Figure 3-5 This is a portion of the first closeup photograph of the moon crater Copernicus, taken by Lunar Orbiter II. The mountains in the background rise 1,000 feet. The distance from the horizon to the base of the photograph is about 150 miles.



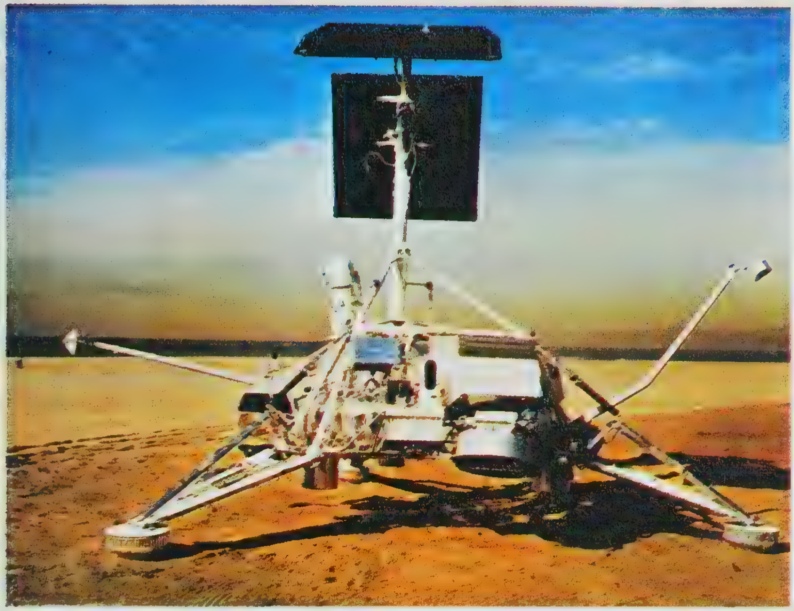


Figure 3-6 A Surveyor moon probe, a forerunner of the Apollo program, was designed to investigate the moon environment for a future manned landing.

know it will be found on the moon. Of course, this cannot be confirmed until we can examine the moon more closely. The United States, as a result of the Apollo Space Program, landed two men on the moon in July 1969.

The possibility of finding life on Mars is greater than on the moon. Although the thin Martian atmosphere is not the same as ours, it does contain some water and oxygen. Experiments have confirmed that some simple forms of life can survive under the conditions that we think exist on Mars.

Our observations indicate that much of what we know about geology on the earth will help us in our studies of the geology of the moon and Mars. We feel sure that the laws of nature on the earth will also be the laws of the other planets and satellites. For this reason, the chemist and physicist have a great interest in learning more about these bodies in space.

Here is an example of a whole new field of science in development. Space science includes fields such as astrophysics, astrogeology, and exobiology. All these branches of science are interrelated, as are the earth sciences. Specialists in these fields are dedicated to learning all they can about the environment of space.

Study Guide

1. Explain how the early astronomers decided whether an object was a planet or a star.
2. Why did the early astronomers believe the earth was the center of the universe?
3. To which galaxy does the sun belong?
4. Why do planets sometimes appear to move backward?

3-3 THE EARTH AS A WHOLE

On the average, the earth is about 150 million kilometers from the sun. We know that the earth rotates on its axis and that one full rotation is called a day. Man has divided each day into 24 hours, each hour containing 60 minutes, and each minute containing 60 seconds.

Hours, minutes, and seconds are artificial divisions of time, invented by man. The day is real, since the earth does rotate. The earth revolves around the sun once in a period of time we call a year—365.24 days. This period is also real. Man cannot change the length of the day or the year. He can change the smaller units of time, and the length and number of months in a year.

We know that the surface of the earth is not uniform. There are three major divisions of the surface—continents, oceans, and atmosphere. The ocean basins are relatively shallow depressions in the surface of the earth and are filled with

Figure 3-7 This photograph of Africa and Europe shows the Straits of Gibraltar. It was taken by Gemini X.

salty water. About 71 percent of the earth's surface is covered by ocean. We are not sure where the water came from. The best guess seems to be that most of the water was released when the rocks of the ancient earth were forming. The formation of water occurred so long ago that there is little real evidence to guide us.

New water is still reaching the surface of the earth and finding its way into the oceans. For example, when volcanoes erupt, much of the gas that escapes from them is water vapor. This water is a part of the deep rocks at the roots of the volcano.

Man has measured the earth and found that it has an equatorial circumference of about 40,000 kilometers (25,000 miles) and a radius of about 6,400 kilometers (4,000 miles). Because the earth is spinning, the polar radius (the distance from one of the poles to the center) is a little shorter than the equatorial radius (the distance from a point on the equator to the center). The distortion of the earth's roundness can be seen in the picture at the beginning of this chapter.

Most of us think of the earth as being very rigid, and it is. It is just as rigid as steel. But we know that by applying sufficient force to a piece of rigid steel, we can bend and shape it. This is also true of the earth.

When a car drives through a mud puddle, all the mud does not stick to the wheels. As the wheels spin, the loose mud flies off. This is the result of what is called the **centrifugal effect**. This centrifugal effect, diagramed in Figure 3-8, also occurs for the earth. Near the poles, the earth is turning very slowly and there is little centrifugal effect. At the equator, however, the surface of the earth is moving around its axis at more than 1,600 kilometers per hour (1,000 miles per hour). Therefore, the centrifugal effect is great at the equator. Spinning causes the earth's surface to be forced away from its center.

Figure 3-8 The centrifugal effect around a wheel can be compared to the same effect for the earth at its equator. The mud flying from the tire would correspond to the earth's surface bulging at the equator.

Fortunately, the force of gravity, which pulls toward the center of the earth, counteracts the centrifugal effect. The force of gravity prevents the earth from breaking apart at the equator. Instead, the earth tends to flatten a little at the poles and bulge a little at the equator. Thus, the earth is not shaped like a perfect sphere but is slightly out-of-round.

The highest mountain on the continents is Mount Everest, in Asia. It reaches about 8.8 kilometers (5.5 miles, or 29,098 feet) above sea level. The deepest parts of the oceans extend down about 11 kilometers (7 miles, or about 36,000 feet) from the surface. Such heights and depths seem enormous to us,

but they are small in comparison to the earth's diameter, which is about 12,800 kilometers. Viewed from space, the earth appears to be a smooth ball.

Study Guide

1. Explain why man can change the length of some units of time but not others.
2. Explain why the surface of the earth looks very smooth when photographed from the moon.
3. How is the centrifugal effect important in determining the shape of the earth?

3-4 "WEIGHING" THE EARTH

In order to "weigh" the earth, scientists first had to determine several other quantities. They had to know its **volume** —how much space it occupies. The problem of estimating the volume of the earth was not difficult to solve. An early attempt to compute the earth's size was made by Eratosthenes, a Greek, in about 200 B.C. Figure 3-9 shows how he made the computation. About 150 years ago, a group of French scientists decided to measure the circumference of the earth. They computed both the polar and the equatorial distances around our planet. The average circumference was found to be 39,776 kilometers (24,860 miles).

From geometry, we know that the circumference of a circle is equal to *pi* times the diameter; *pi* is approximately 3.1416.

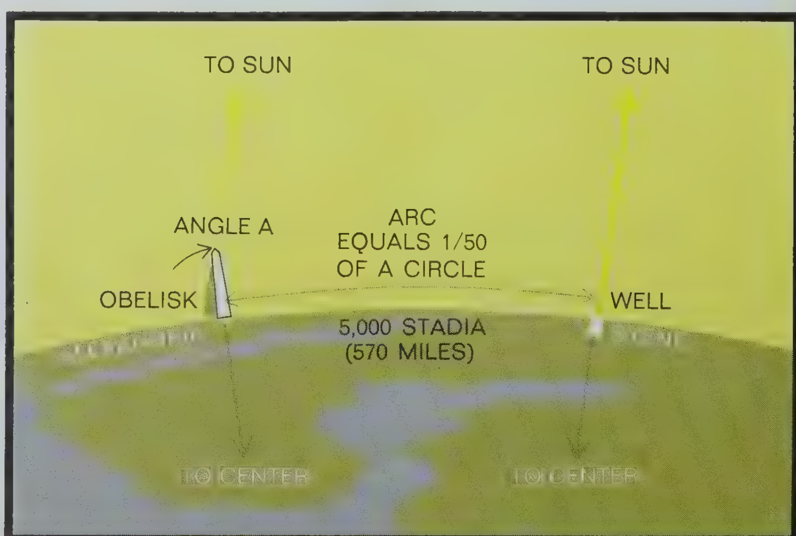


Figure 3-9 Eratosthenes measured the circumference of the earth using the assumptions that the earth is a sphere and the sun's rays are parallel. He learned that the bottom of a well at Syene was completely lit up by the sun at noon on a certain day when the sun was directly overhead. On this same day at noon in Alexandria, 5,000 stadia from Syene, an obelisk cast a shadow because the sun was not directly overhead. From the angle of the shadow he realized that the distance from Alexandria to Syene represented one-fiftieth of the circumference of the earth. Therefore, he estimated the earth's circumference was 50 × 5,000, or 250,000 stadia (about 46,250 kilometers), which is close to modern measurements.

Writing this as an equation, we have $C = \pi d$. If we substitute numbers for the symbols, we have $39{,}776 = 3{,}1416d$. Solving this equation, we find that d, the diameter of the earth, equals 12,661 kilometers (7,914 miles). The radius is equal to one half the diameter, or 6,330 kilometers (3,957 miles). By using the geometric equation for the volume of a sphere and the computed radius of the earth, an approximate volume for the earth is found. This turns out to be 11×10^{11} cubic kilometers (24×10^{10} cubic miles).

The accepted value for the radius of the earth is 6,378 kilometers (3,963 miles).

Volume of a sphere equals $4/3$ *pi* radius cubed.

It is interesting to note that the metric system is based on an earth measurement. At the end of the eighteenth century, French scientists defined a new unit of length, the meter, as one ten-millionth of a meridian running from the equator to the North Pole. The scientists specified the meridian passing through Paris (see Figure 3-10).

Another problem that scientists faced was how to determine the mass of the earth. The mass of an object is not the same as the weight of the object. The mass never changes unless the amount of matter in the object changes. We can find the mass of an object by putting it on a balance scale and then balancing its mass against a mass of known value. You can see that such a method is impossible to use with the earth.

Figure 3-10 A quadrant of the earth from the equator to the North Pole is the basis for the meter. A quadrant is equal to 10 million meters.

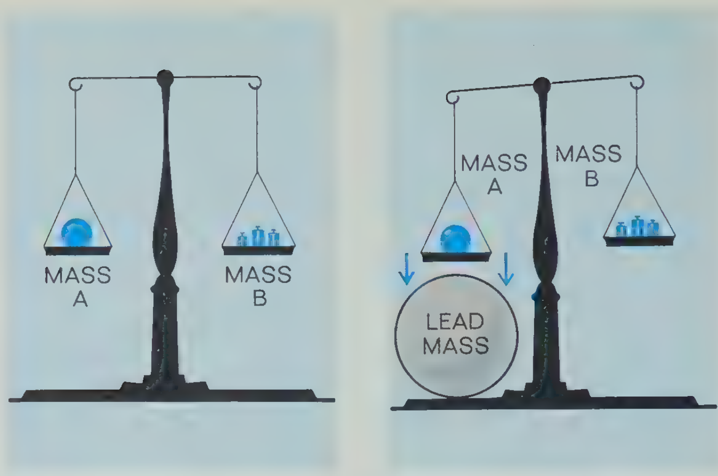


Figure 3-11 Von Jolly's apparatus for massing—"weighing"—the earth

Mass and weight are different attributes of matter. The mass of an object never changes, whereas weight depends on the gravitational attraction on a mass. For example, your weight is greater on the earth than it would be on the moon because the gravitational attraction of the earth is greater than that of the moon.

The **weight** of an object is the effect of gravity on its mass. Your weight is equal to the force with which gravity is pulling your mass down. Newton determined this fact almost three hundred years ago. How can we use it to determine the earth's mass?

Philipp von Jolly, a German physicist, devised an ingenious way to "weigh" the earth, based on Newton's studies of gravity. Von Jolly built a large balance scale (see Figure 3-11). On the left pan of the balance he put a large mass and balanced this with accurately measured masses on the other pan. The masses on both pans were equally affected by the earth's gravitational attraction. This is why they balanced each other.

He then moved several tons of lead under the left pan, which held the large mass. The combined force of gravity of the earth and of the lead mass caused the left pan to be heavier and therefore out of balance with the known masses. When the two pans were again brought into balance by adding known masses to the right pan, Von Jolly had all the experimental data he needed to estimate the mass of the earth.

The *gain* in weight of the object on the left pan was caused by the force of gravity exerted by the lead beneath it. Von Jolly then used Newton's equation for determining the force of gravity to estimate the mass of the earth (see Section 2-3). By this method he computed that the earth has a mass of 5.98×10^{27} grams.

The density of the earth is another value that interests scientists. The definition of **density**, as used by scientists, is

the mass in grams of 1 cubic centimeter of a substance. Written as an equation, it is

$$d \text{ (density)} = \frac{m \text{ (mass)}}{v \text{ (volume)}}.$$

Therefore, the density of the earth must be

$$d = \frac{5.98 \times 10^{27} \text{ grams}}{1.083 \times 10^{27} \text{ cubic centimeters}}.$$

Since 10^{27} divided by 10^{27} is 1, the density of the earth is

$$\frac{5.98 \text{ grams}}{1.083 \text{ cubic centimeters}}.$$

The result of this division is about 5.52 grams per cubic centimeter. This measurement is an average density for the whole earth. The various kinds of earth substances have different densities.

The earth is quite dense as compared with the other planets. We can divide the planets of the solar system into two groups: the inner group—Mercury, Venus, Earth, and Mars—and the outer group—Jupiter, Saturn, Uranus, Neptune, and Pluto. The inner planets are small, and the outer ones, with the exception of Pluto, are large. The inner planets are composed of quite dense matter, whereas the outer ones are composed of much lighter stuff.

We suspect that the other inner planets are made of materials similar to those that compose the earth. We do not have a very good idea of the materials that compose the outer planets. Our estimates of the densities of the planets have been made by applying what has been learned of physics on the earth.

3-5 FROM NORTH AMERICA TO THE WORLD

As you study earth science in this book, you will find that most of the examples are from North America. This does not mean that less is known about the other continents. However, we believe that since you live in North America, you should know most about it.

The forces that cause things to happen on the crust of the earth are the same everywhere. What you learn from studying North America can be applied to any continent. That really is what all scientists are trying to do. They try to explain phenomena so accurately that their explanations will hold true everywhere. When an earth scientist tries to explain how a

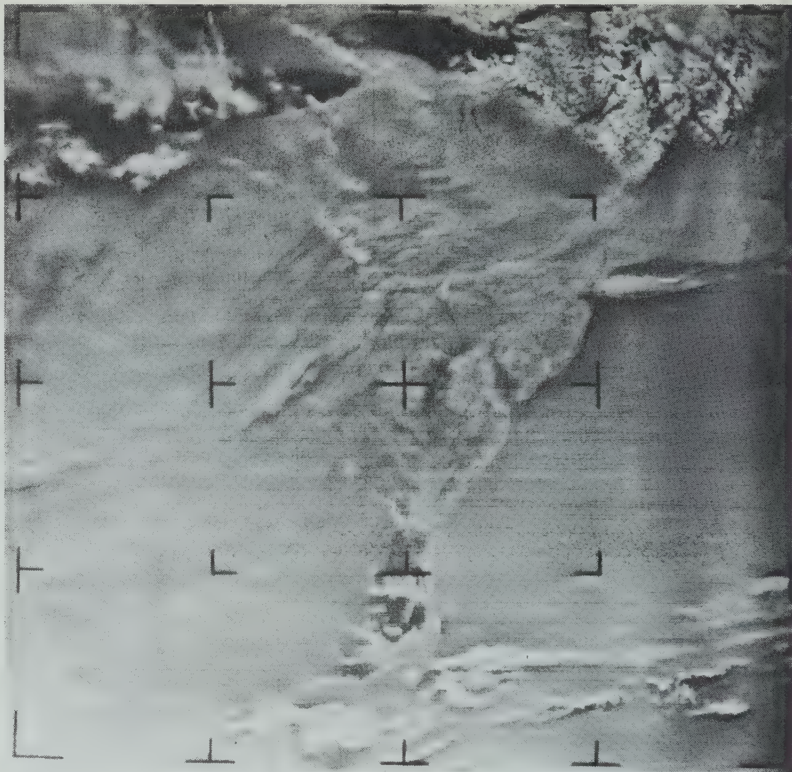


Figure 3-12 Northeastern United States from space

volcano acts, that explanation should apply to any volcano on the earth. We also think it should apply to a volcano on the moon or on Mars.

Study Guide

1. How was the earth first "weighed"?
2. What is density? From your own experience, name a material with a high density and one with a low density.
3. Why is 5.52 grams per cubic centimeter the *average* density of the earth?
4. In what ways do the inner planets differ from the outer planets?

SUMMARY

Our ideas of the place and importance of the earth in the universe have evolved very slowly. Earth is a small planet associated with an average-sized star in a galaxy that is one of billions. Until recently, there was little general interest in the other planets of the solar system, except among astronomers. Now, with the possibility of space travel, there is renewed interest in the moon and the nearer planets, especially Venus and Mars.

During the past century and a half, scientists have devised methods that have enabled us to measure the earth. We know that it has an average radius of about 6,330 kilometers, a mass of 5.98×10^{27} grams, and an average density of 5.52 grams per cubic centimeter. It rotates on its axis once in a day and revolves around the sun once in a year. The day and the year are the only real measures of time.

REVIEW AND DISCUSSION QUESTIONS

1. How does space travel depend on Newton's discoveries about gravity?
2. Which person is moving faster, one standing still in Chicago or one standing still on the equator? Explain your answer.
3. What would happen to your weight and the weight of the earth if the force of the earth's gravity were decreased by one half?
4. Convert the following to powers of 10: 4,000 miles; 93,000,000 miles; .0000003 centimeter.
5. Which weighs more, a pound of rock or a pound of feathers? Which has a greater density? Explain.
6. Kepler's third law of planetary motion states that the greater the distance between a planet and the sun, the longer the planet's period of revolution. Why is this so?
7. You can tie an open can of paint to a rope and twirl it around your head without spilling a drop. Explain why.
8. The planet Jupiter has a density of 1.3 grams per cubic centimeter. Earth's density is 5.52 grams per cubic centimeter. A person weighing 100 pounds on the earth would weigh 265 pounds on Jupiter. Discuss the reasons for this difference.


A
A
B

CHAPTER 4

THE BEGINNING OF GEOLOGY

Man has always been interested in studying the earth, although it is only recently that he has made a formal science of it. When primitive man began to make tools from stones, he must have learned something about what we now call geology. He learned that some stones were better than others for making spear points, knives, and scrapers. Some of these early tools are shown in Figure 4-1. It was an advantage for man to be able to tell the difference between types of stones and to know where they could be found.

4-1 THE USE AND UNDERSTANDING OF EARTH MATERIALS

When man discovered that some kinds of rocks are easy to quarry, he began to build permanent buildings of stone. He split the rocks from rock ledges and shaped them by hammering them with harder stones. Other kinds of rocks did not split and shape easily, so they were difficult to use for building purposes. In Greece and Egypt in the Old World and in Mexico and Peru in the New World, men built beautiful buildings of stone, using only stone tools. Some of these buildings are covered with carved designs.

It took man a long time to discover that superior tools could be made of metal. The only uncombined metals found near the earth's surface are gold, silver, copper, and very rarely a little iron in the form of meteorites. Both gold and silver are much too soft and too rare to be used for tools.

Copper may have been used first in the region near the Suez Canal, between Africa and Asia. Very old mines from which copper and copper ore were once extracted have been found on Mount Sinai, in the Sinai Peninsula. Copper was first used to make ornaments and implements for religious ceremonies. This is what men had done with the gold and silver found in streams. Later, men learned that if they mixed

An illustration from Agricola's *De re metallica* shows miners at work during the Middle Ages.

tin with copper, a hard metal called bronze was produced, from which useful tools could be made. The early Indians living near Lake Superior found much copper, but they never learned how to make it hard enough to be used for tools. They, too, used it only for ornaments and ceremonial objects.

About four thousand years ago, men who lived in the Old World learned how to make tools of iron. Now men could make strong tools with which to improve their way of living. This profoundly changed the course of man's progress. It is difficult for us to think of living in a world without iron. In the New World, at the time the Spanish explorers came to America, men had still not discovered how to extract iron from its ores. That was a little more than 450 years ago.

We give the general name **ore** to any substance from which valuable materials can be extracted economically. When ores containing some metals are crushed, and heated with carbon, a chemical reaction takes place that liberates the useful metal. This process is called **smelting** (see Figure 4-3).

Figure 4-1 Stone Age man used animal bones and various types of rocks to fashion spears and arrowheads.

4-2 KNOWLEDGE OF THE EARTH IS RECORDED AND TAUGHT

As man became more civilized, he found that he needed to know more and more about the earth. In ancient Greece and

Most metals are found as complex combinations of many elements.

Figure 4-2 The Temple of the Warrior at Chichén Itzá is an ancient Aztec temple. Hand-quarried stone was used to build the temple.

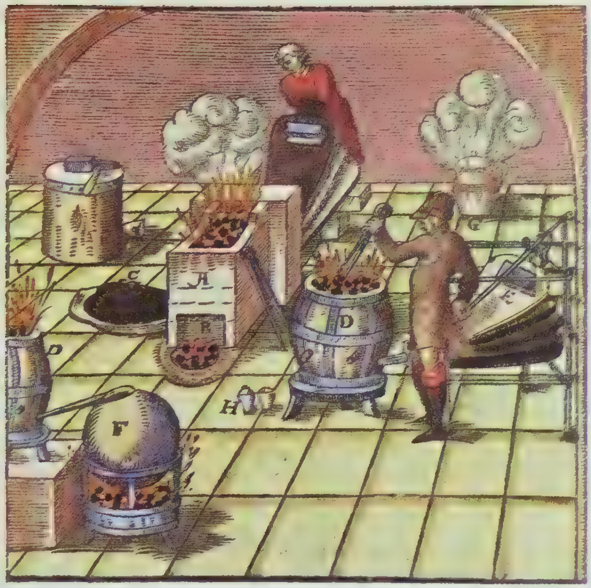


Figure 4-3 This sixteenth-century copper factory in Europe closely resembled an alchemist's laboratory: A) small smelting oven; B) furnace; C) crushed ore; D) testing oven; E) bellows; F) spherical water tank; G) melting pot for alloys; H) testing crucible.

Figure 4-4 Today we use carbon in the form of coke to extract metals from their ores. However, there are some metals, such as aluminum and magnesium, that cannot be extracted in this manner. Other methods, such as electrolysis, are used.

China, scholars recorded observations about the land. They studied the mountains and rivers. They learned that earthquakes usually accompany volcanic activity. They learned that when rivers flood, a deposit of rich soil is left behind on the flooded land. Observations of this kind ultimately led to the beginnings of geology.

electrolysis (ee lek TROL uh sis); Latin: *electricus*, produced by friction + *lysis*, loosening. The process of separating chemicals by the passage of an electric current.

Aristotle, a Greek natural philosopher who lived in the fourth century B.C., organized and recorded what was known to him about the earth. This record was used as a textbook for more than fifteen hundred years. Aristotle's writings influenced scientific thought for more than two thousand years. Today we have found better explanations for some of the phenomena Aristotle observed and tried to explain. The fault with Aristotle was that he did not test his hypotheses. The replacement of old ideas by new ones is not uncommon in science. When an explanation becomes unsatisfactory because of its disagreement with reality, it must be discarded and replaced by a new one.

Study Guide

1. Explain why men first became interested in what we now call geology.
2. Name the metals first used by man, and state their uses.
3. Explain why civilization progressed more rapidly once man learned how to smelt iron ore.
4. State how Aristotle's approach to science differed from the one used today.

4-3 WERNER TEACHES MINING

Figure 4-5 Abraham Werner (German, 1750–1817). Werner learned much about mining from his father, the Inspector of Iron Works in Freiberg, Germany. He advanced the theory that all rocks were precipitates of the primeval ocean.

Many of the old ideas about geology were not discarded until the end of the eighteenth century. The last great teacher of the old-fashioned geology was Abraham Werner (see Figure 4-5). In 1775, at the age of twenty-five, Werner became a teacher at the Freiberg Academy of Mines in Germany, where he had been a student. Eventually, he was considered the best teacher of mining in Europe. His teachings were based chiefly on what Aristotle had written.

Werner began to teach many things about the earth's structure that he had not tested and proved. He only thought these ideas were true. He taught that the earth was once covered entirely by water. From this water, rocks were formed into mountains, valleys, and plains. Then something happened, causing the water to drain away, leaving continents, islands, and oceans. Werner believed this had happened several times. Each time that water covered the entire earth, a new set of rocks was formed.

Even though Werner had little or no evidence for his theory, his students accepted it as though it had been proved. No one dared to ask him, "Where does the water go when it drains off the earth?" or, "How can water change into rocks?" Werner never explained how such things could happen.

4-4 HUTTON CHANGES THE STUDY OF GEOLOGY

A few people interested in the origins of rocks doubted what Werner was teaching. One of these was James Hutton, a Scotsman. As a farmer, Hutton worked with soil and rocks, and he began to wonder how they had been formed. He observed the action of streams that ran through the valleys near Edinburgh, and he saw that the running water moved dirt and pebbles downstream. He believed rivers cut into the rocks of hills and mountains and carved valleys. He watched the action of sea waves as they pounded against the shore,

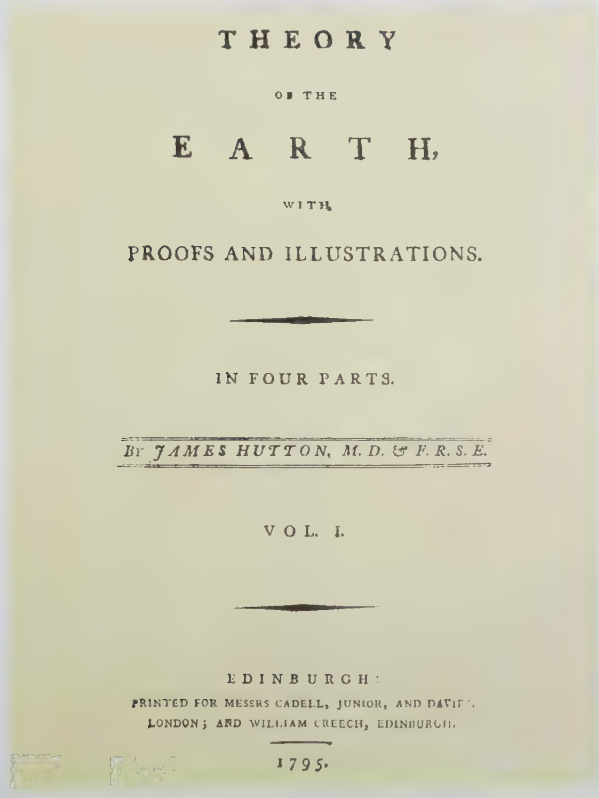
and he became interested in the way moving water carried sand and pebbles. These observations gave him ideas about how valleys and beaches were formed.

Hutton's ideas were quite different from the ones Werner taught. He liked to discuss his ideas with a few friends, and in 1795 he published a book called *A Theory of the Earth, with Proofs and Illustrations.* Hutton presented a theory based on evidence. The publication of his book about the earth started arguments that divided the geologists of that time into two groups.

Figure 4-6 James Hutton (Scottish, 1726–1797). Before becoming a farmer, Hutton worked in a lawyer's office and later went to medical school. Returning to Edinburgh, he found that there was no need for a young doctor, so instead of practicing medicine he bought a farm. He successfully applied to farming the scientific methods he had learned in medical school. Hutton tried to trace the origins of various minerals and rocks in order to arrive at a clear understanding of the history of the earth.

4-5 THEORIES BASED ON EVIDENCE, NOT ON MAGIC

It is important to learn what Hutton's basic ideas were because they formed the beginnings of modern geology. Hutton believed geologists must explain what has happened on the earth only on the basis of observable facts. To do this, they must use their own observations and those of others, not only in geology but also in physics and chemistry.



THEORY

OF THE

EARTH,

WITH

PROOFS AND ILLUSTRATIONS.

IN FOUR PARTS.

By JAMES HUTTON, M. D. & F. R. S. E.

VOL. I.

EDINBURGH:

PRINTED FOR MESSRS CADELL, JUNIOR, AND DAVIES, LONDON; AND WILLIAM CREECH, EDINBURGH.

1795.

Figure 4-7 Unfortunately, Hutton's book was written in a style that was difficult to read. A few years after it was published, John Playfair, a young friend of Hutton's, rewrote the book in clearer language. He called his book *Illustrations of the Huttonian Theory*. Originally printed in 1802, it has recently been reprinted as a paperback.

Before Hutton stated his ideas, people thought changes on the surface of the earth happened very quickly. They thought that every so often in the past everything on the surface of the earth was destroyed and the oceans rose over all the land. Then the oceans drained away and the land reappeared, with new mountains and river valleys already formed. Hutton did not believe this, because he could find no way to explain how the water could appear and disappear rapidly.

Hutton had seen how water carried away soil from his land. He believed the whole work of carving a valley was done by the streams in the valley. Werner did not explain how valleys could have been formed, but Hutton did. It seemed more logical to Hutton that changes on the surface of the earth took place very slowly and were caused by natural forces that could be observed. These new ideas were better because they were based on observations of stream action in valleys.

4-6 HUTTON'S IDEA ABOUT ROCKS

Werner taught that certain kinds of rocks were formed from seawater. These he called "secondary rocks" (see Section 5-1). One of Werner's secondary rocks is what geologists today call **sandstone**. This is a rock composed of layers of sand grains that are cemented together.

Hutton explained how such a rock could be formed from material carried from the land by running water. He had watched the action of moving water in streams and along the coast of Scotland. He saw how the currents in the sea arranged the sand grains brought there by streams. The sand was deposited in layers, and the finer particles of mud were washed away. Hutton believed that in time the layers of sand grains in the sea became cemented and formed the sandstone. The sand and the mud carried by a stream is called **sediment**, and the rocks formed from sediments are called **sedimentary rocks.**

Hutton saw how another of Werner's secondary rocks could be formed. Where a river flows into the sea, mud is dropped on the bottom in thin layers when there is little water movement. He believed this thinly layered mud was in time changed into the rock called **shale.** This is a rock made up of thin layers of very fine mud particles, finer than the finest sand grains. The individual particles are so small that you can see them only by using a strong magnifying lens. Figure 4-8 shows sandstone and shale.

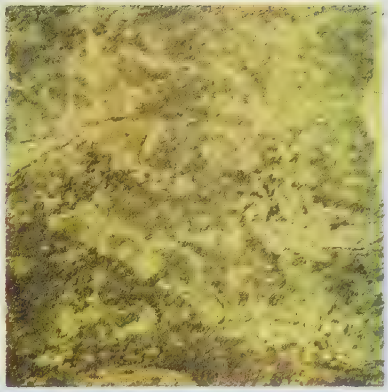


Figure 4-8 Sandstone (*left*) and shale are two types of sedimentary rocks. Shale is the most abundant sedimentary rock found on the continents.

4-7 EVIDENCE FOR UP-AND-DOWN MOVEMENT OF THE LAND

Hutton visited places on the east coast of England where the land had sunk beneath the sea. In a shallow bay, he saw the trunks of dead trees standing upright under the water. There the land obviously had sunk in relation to the sea. In other places, far above the present seashore, he saw seashells in rocks, such as those shown in Figure 4-9. He reasoned that these shells must be the remains of animals that had lived in the sea. They could not have lived on dry land.

These observations led Hutton to believe that the land was not always stationary but that it could move up and down in

Figure 4-9 These fossil corals are imbedded in weathered, iron-stained limestone of the Middle Devonian Period. They were found at the falls of the Ohio River at Louisville, Kentucky.

relation to the sea. When the land rose, it lifted the sedimentary rocks, which had been formed at the ocean bottom, above the level of the sea. In these rocks were the shells of sea animals that had been buried in the sediments. Before the land rose, the shell-bearing sediments had been changed to sedimentary rocks. We know today that there are changes in the relationship between sea level and the land.

4-8 WHAT HAPPENS NOW PROBABLY HAPPENED IN THE PAST

Hutton's ideas changed the way geologists explained what had happened and what is happening to the earth. He would not allow mysterious and unknown actions to be used as explanations. Hutton believed that observations of what is happening in the present should be applied to what had happened in the past. This basic idea that Hutton contributed to geology is an important one. It has been called the **principle of uniformitarianism**. As scientists learn more about what is happening today, they can better explain what has happened in the past.

Uniformitarianism is the belief that uniform geologic processes have occurred throughout the earth's history.

New ideas began to take form in biology at about the same time that Hutton was developing new ideas about geology. The ideas most useful to geology were those about the evolution of modern plants and animals.

Hutton's idea about rocks being formed from sand and mud in the sea also helped biology. For years, people had found curious objects in rocks—objects that looked like seashells, animal bones, and pieces of plants. The people who believed Werner's ideas thought these objects were just curious forms of rocks. The people who believed Hutton's principle of uniformitarianism reasoned that these strange objects were the remains of animals and plants that had been buried in sand and mud. Because they dug such objects out of rocks, they called them **fossils.** As more was learned about the fossils found in rocks, it was discovered that they could be used to determine the age of the rocks and the history of living things.

fossil (FOS ul); Latin: *fossilis*, dug up.

Study Guide

1. Who was Abraham Werner, and in what branch of earth science did he specialize?
2. Explain how Hutton's studies changed the ideas about the way things happen to the earth.
3. Give some evidence that suggests that some parts of the earth now on land were once under the sea.

4. Name two kinds of sedimentary rocks.
5. State what you understand to be the meaning of the term *uniformitarianism.*

SUMMARY

The invention of stone tools by man was followed by man's recognition of the various properties of different kinds of rocks. Later, the use of metals extracted from ores made it possible for civilization to progress more rapidly than it had when stone tools were used.

The work of Aristotle influenced scientific thought for more than two thousand years. Abraham Werner was the last of the well-known teachers of geology to be strongly influenced by Aristotle. Modern earth-science principles are based on work done by James Hutton during the last decades of the eighteenth century. Hutton's greatest contribution to science was probably his insistence on explaining phenomena in the light of tested scientific ideas. He believed the processes that occur on the earth today also took place in the past.

REVIEW AND DISCUSSION QUESTIONS

1. Explain how man first came to learn the difference between types of stones.
2. Why was it so long before man began to make his tools out of metal?
3. Describe the relationship between tools and civilization.
4. To what use did man put the first metals known to him?
5. How was the process of smelting probably discovered?
6. What occupation led to the beginnings of geology?
7. To be a successful scientist, what must one do besides study and think?
8. Explain why Werner's ideas about geology have been discarded.
9. What must acceptable scientific theories be based on?
10. What is the difference between mud and sand?
11. What evidence is there for the theory that the land rises and sinks in relation to the sea?
12. Essentially, the principle of uniformitarianism requires that all phenomena be explained by existing laws of science. Explain why this is one of the most important rules a scientist must follow.

CHAPTER 5

PILES OF ROCKS

For a long time, men have noticed that there are many kinds of rocks. The study of rocks is the branch of earth science called **petrology**. When men began to organize what they knew about rocks, they discovered that rocks could be classified into two or three general groups. But the more men learned about rocks, the harder it was for them to decide to which group a particular rock sample belonged. Until you can easily identify rocks in general, you must assume that the features we describe can always be seen. As you learn more about rocks, you will see for yourself that the first simple descriptions will have to be modified.

5-1 BOTTOM AND TOP ROCKS

The early petrologists found that in some places sedimentary rocks, such as sandstone and shale, rest on top of very different kinds of rocks. These basement rocks, lying beneath the sedimentary rocks, are usually composed of interlocking crystals of several kinds of minerals (see Section 1-6). Usually, the individual crystals are large enough to be seen without a magnifying lens. Because these rocks are composed of a variety of crystals, they are called **crystalline rocks**.

Whenever one reaches the bottom of a series of layers of sedimentary rocks, as in the Grand Canyon, crystalline rocks are found beneath the sedimentary rocks. (A series of sedimentary rocks is shown in the picture at the beginning of this chapter.) Observations like this led Werner to reason that sedimentary rocks are always younger than crystalline rocks, since they are found on top of them. That is probably why he called the sedimentary rocks "secondary rocks" and the crystalline rocks "primary rocks."

When objects are placed one on top of the other, they form a **sequence**. If you pile all your books on your desk, the first

Layered deposits of coal and sandstone, Coal Canyon, Arizona

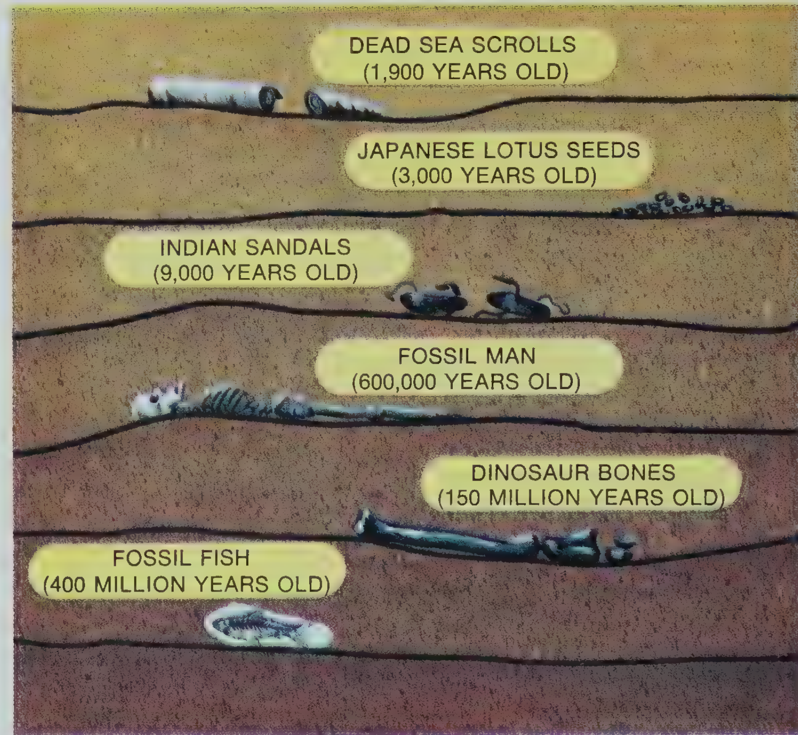


Figure 5-1 The objects found lower down in these layers of sediments are older than those found near the top. This is the principle of superposition. Does this principle always hold true?

The area that is now the Grand Canyon was ocean bottom millions of years ago.

one you put down will be in the pile longer than any other. It is the oldest one in the sequence. It is also the bottom one in the sequence. So time and position both play a part in the idea of a sequence.

Both Werner and Hutton noticed, as had many men before them, that sedimentary rocks are found in a sequence of position. Both of them believed this sequence to be related to time. They believed the top layers of the sequence were younger rocks than the bottom layers. This idea is a useful one, and we have found no reason to replace it with another. We call it the **principle of superposition** (see Figure 5-1).

5-2 RIVERS DROP THEIR SEDIMENTS

debris (duh BREE); French: *debriser*, to break into pieces.

Hutton had watched the way moving water carries mud, sand, and pebbles and finally deposits them in the sea. He saw rivers carry great loads of debris. Debris such as that shown in Figure 5-2 is made up of everything that is washed

from the land into a river. Grass, leaves, and branches of trees float when washed into a river. The mud, sand, and pebbles eventually settle to the bottom. The latter kind of debris, you remember, we call sediment.

When rivers flow very rapidly, they stir up sediment, and the water becomes cloudy with mud. In this way, sand and pebbles are separated from the mud, and the mud is washed away. Hutton saw that the streams in the mountains washed the mud out of the debris very rapidly. The tiny particles of mud were actually carried, or **suspended**, in the water. When he watched through clear water, he saw that sand and pebbles were also moved downstream, but these particles slipped and rolled along the bottom. Why should mud particles be carried differently than sand and pebbles are carried?

A suspension is a combination of a fluid and a solid in which the particles are not dissolved in the fluid and do not readily settle to the bottom.

5-3 SEDIMENTS SETTLE OUT

When Hutton was at the seashore, he observed what happens to the debris carried by a river as it enters the ocean. The river slows almost to a halt, and the debris it has been carrying settles to the bottom of the sea as sediment. (Read the experiment in the margin.)

Stir some soil in a glass of water. You will see that the first pieces to settle are the largest. As the water slows down, smaller and smaller pieces settle out.

Figure 5-2 Debris left after a flood

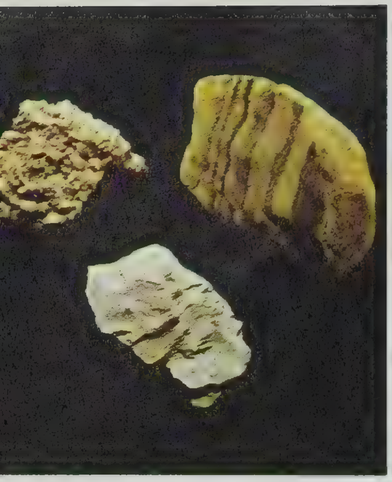


Figure 5-3 Some conglomerates may be formed by streams in which the velocity of the water keeps changing. How would this action leave a sediment that might become a conglomerate? (*Upper left*) conglomerate; (*upper right*) sandstone; (*bottom*) shale.

conglomerate (kun GLOM ur it); Latin: *conglomerare*, to roll together. A rock formed of different-sized particles cemented together.

Now relate the stirred glass of water to a moving stream. As a stream slows down, the larger particles settle out, but the smaller ones continue to be carried by the stream. The slower the stream moves, the smaller are the particles it can carry with it.

Since at any one place in a stream the water is moving at a steady speed, particles that are more or less uniform in size are dropped. In that way, moving water **sorts** the material it is carrying. The action of the stream also rounds the particles by **abrasion**—that is, by rubbing one upon the other. You may have seen rounded stones near a stream or seashore. They have been rounded by abrasion.

5-4 SEDIMENTATION IN THE OCEAN

In the sea, moving water in the form of waves close to shore sorts the sediments. In some places the movement of the water is so strong that it washes away everything except large stones. Sandy beaches are formed by weaker water action. Where there is hardly any water movement, the shore is likely to be muddy.

Hutton made all these observations. He believed the sediments on the ocean floor were the materials from which sedimentary rocks were formed. We now know that fine mud particles deposited in quiet water produce the rocks we call shale. Sandy deposits produce sandstone. When the spaces between pebbles become filled with mud and sand, pebbly deposits turn into **conglomerates**. These three kinds of sedimentary rocks are shown in Figure 5-3.

Two conditions must exist along the shore in order to produce a conglomerate. First, the area must be exposed to water flowing rapidly enough to wash away the finer particles, thus allowing a layer of pebbles to accumulate. Second, the bed of pebbles must later be washed with water flowing slowly enough to allow sand and mud to settle into the spaces between the pebbles.

Study Guide

1. Explain how the two basic types of rocks differ from each other.
2. Describe the usual relative ages of several rock layers found in a sequence.
3. In your own words, explain the principle of superposition.
4. Describe the effect of moving water on the sizes of particles of sediments.

Figure 5-4 This view shows the results of centuries-old fissure eruptions, volcanic cones, craters, lava flows, caves, and other volcanic phenomena.

5-5 THE SOURCES OF SEDIMENTS

Where do sediments come from? We have seen that streams and rivers carry sediments from the land to the sea. If we look at the upper ends and along the lengths of streams, we should find the sources of the sediments. On the land over which the streams flow, we find soil and rock. Soil is formed on land from rocks that have been broken down by processes we shall study later.

There are many kinds of rocks on the land surface of the earth. Some are old sedimentary rocks that have been lifted above sea level. Others are crystalline rocks, mentioned earlier in this chapter. In Scotland, where Hutton lived, much of the hilly and mountainous country is composed of crystalline rocks. He believed most of the sediments he saw being transported by streams were produced from those crystalline rocks as streams cut valleys into them.

5-6 CRYSTALLINE ROCKS

Many crystalline rocks look as though they had once been molten, or melted. In these rocks we can often see the effect of the flow of the molten rock, as in Figure 5-4. In other cases, the rock looks very much like the slag from a blast

furnace. Heat is needed to melt things. Because we associate heat with fire, some crystalline rocks have been given a name that means "made by fire"; they are called **igneous rocks**. Igneous rocks are not really formed by fire but are formed at high temperatures within the earth.

It is easy to see how a solid rock could be made by melting substances and then letting the molten mixture cool and harden. If we melt copper and zinc together and let the mixture cool, an alloy called brass is formed. In this example, two different substances when melted together form a third substance. That is the way igneous rocks are formed; various minerals are melted together and later cool to form the rock.

Since most igneous rocks lie beneath sedimentary rocks, they are usually older than the sedimentary rocks. An exception is **lava**, which pours from a volcano, flows over sedimentary rocks, and then cools and hardens.

Still other igneous rocks have been squeezed while still molten into spaces between or across layers of older sedimentary rocks. This is called an **intrusion**. Such a feature is shown in Figure 5-5. So you see that igneous rocks can be older or younger than adjacent sedimentary rocks.

Figure 5-5 Although intrusions are formed below the earth's surface, they eventually appear at the surface, as does this one. The rock on either side of the intrusion is less resistant than the intrusion and has been worn away, leaving this formation.

5-7 GRANITE: AN IGNEOUS ROCK

The many kinds of igneous rocks have been grouped and named. They are recognized by their texture and by the minerals they contain. The word *texture* when used to describe an igneous rock refers to the size of the mineral grains found in the rock. A rock having large, easily seen grains is said to have a coarse texture and is called a **coarse-textured** rock.

An igneous rock having small mineral grains, sometimes seen only with a magnifying lens, is a **fine-textured**, or fine-grained, rock. Figure 5-6 shows igneous rocks of both types. Petrologists suspect that large crystals occur because the molten material from which the granite froze (became solid) cooled very slowly and uniformly. **Intrusive rocks** cool slowly underground, allowing time for large crystals to form. **Extrusive rocks**, such as lava, are those that have cooled rapidly while exposed on the earth's surface.

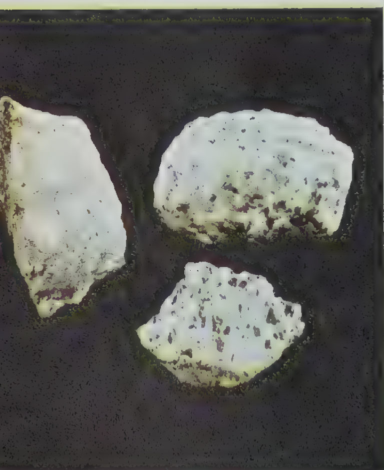


Figure 5-6 In both granite and rhyolite, the cooling takes place at a uniform rate—granite very slowly, rhyolite very rapidly. A porphyry contains crystals of many sizes.

Probably the most common of the coarse-textured igneous rocks found at the surface of the earth is granite. Granite is the solid bedrock of which the continents are made. This is the name of a whole family of rocks, described in Section 1-6, that have certain characteristics in common.

When the same kind of molten mixture that forms granite is thrown out of a volcano or oozes onto the surface through a crack, it cools quite quickly. Therefore, large crystals do not have time to form. Although this very fine-textured rock is composed of the same molten materials as granite, it is formed in a different way—it cools rapidly and therefore has a different appearance than granite. Geologists give it a different name, **rhyolite**.

rhyolite (RYE uh lyet).

Sometimes the molten mass cools irregularly. Then the mineral grains are not all the same general size. Such rocks have a curious texture. The crystals of some of the minerals are small, while others are large. Usually the large grains are feldspars. Such a rock is called a **porphyry.**

porphyry (PAWR fur ree).

5-8 OTHER IGNEOUS ROCKS

There are other families of igneous rocks. A second family, which is often associated with volcanoes and lava flows, is the **basalt** family. These rocks lack quartz. They contain more iron-magnesium minerals than granite does, and are very dark in color (return to Figure 5-6). In addition, basalts often contain some plagioclase, a feldspar that contains calcium.

plagioclase (PLAY jee uh-klays).

Usually, basalts are fine-textured because they solidify at the surface of the earth and cool quickly. They differ markedly from the granites, which are light-colored, coarse in texture, and less dense.

diorite (DYE uh ryet).

A third family of igneous rocks are the **diorites.** These are rather light-colored and are composed largely of plagioclase and hornblende but no quartz. Thus, they are intermediate between granites and basalts in color, texture, and density. Those of you who are interested in learning more about the families of igneous rocks will find an outline of them in Appendix II.

Study Guide

1. What does the word *igneous* imply?
2. Under what conditions would you find igneous rocks that are younger than neighboring sedimentary rocks?
3. Explain why two igneous rocks may have the same mineral composition but different-sized grains.
4. Name the two main minerals that always make up granite (see Chapter 1).
5. What is a porphyry?
6. Which rock is darker, granite or basalt? Why?

5-9 IGNEOUS AND SEDIMENTARY ROCKS CAN CHANGE

There is a third class of rocks, which is related to the igneous and sedimentary. This class is made up of rocks that were once either igneous or sedimentary but have been changed. They are called **metamorphic rocks**. **Metamorphism** can be caused by heat, pressure, bending, chemical action, or combinations of these. One of the results of this change is the development of interlocking crystals. Therefore, metamorphic rocks are considered crystalline rocks, as are the igneous rocks.

metamorphism (met uh MAWR fiz um); Greek: *meta*, change + *morphe*, form.

We are just beginning to learn how metamorphic rocks are formed. We need to know what happens in a solid when it is heated and compressed to fully solve the problem. It appears that the change takes place without the original rock being actually melted or dissolved.

It is sometimes difficult for geologists to determine whether certain types of crystalline rocks were originally igneous or metamorphic.

5-10 SHEETS OF METAMORPHIC ROCKS

Since metamorphic rocks are formed from other rocks in so many ways, there are many ways to classify them. Probably the best thing to do is to separate the metamorphic rocks into two groups: (1) **foliated rocks**, which can be split into layers, and (2) **nonfoliated rocks**, which break into sharp and angular pieces.

foliated (FOH lee ayt id); Latin: *folium*, leaf.

Another way of classifying metamorphic rocks is by the size of the mineral grains that compose each kind of rock.

Figure 5-7 In most old schools, the chalkboards are made of slate. There are many kinds of schist. Their names are formed by combining the word *schist* with the name of the most important mineral present—for example, micaschist. In gneiss you can usually see streaks that are rich in mica, feldspar, or quartz. (*Upper left*) gneiss; (*upper right*) schist; (*bottom*) slate.

These may be so small that one can see them only through a microscope. At the other extreme, they may be so coarse that one can recognize them easily without a lens.

Three common foliated metamorphic rocks are slate, schist, and gneiss, shown in Figure 5-7. **Slate,** which was originally shale, is usually uniformly dark in color and extremely fine in texture. It splits very easily into thin and generally uniform sheets.

Schist will also split easily but not into large, uniform sheets. Instead, the flakes are usually small and irregular. Schist is also different in that the mineral grains, especially the micas, are quite large and can easily be recognized without using a lens. For this reason, the rock has a shiny surface. Because the mineral grains are so large, schist is not uniform in color but speckled.

Gneiss, usually formed from granite, is the third kind of foliated metamorphic rock and the most common. Although gneiss and schist are both metamorphosed from rocks such as granite, they are formed in different ways. Gneiss is a firm rock; it usually does not crumble or break as easily as schist.

gneiss (nyes).

Of the nonfoliated metamorphic rocks, two are especially important—quartzite and marble. **Marble** is metamorphosed limestone, or calcium carbonate. **Quartzite** is metamorphosed sandstone.

Marble and quartzite are formed in the crust of the earth at relatively low temperatures and pressures as compared with other metamorphic rocks. For example, much less heat and pressure are needed to change limestone to marble than to change rhyolite into mica schist. You will find more about metamorphic rocks in Appendix II.

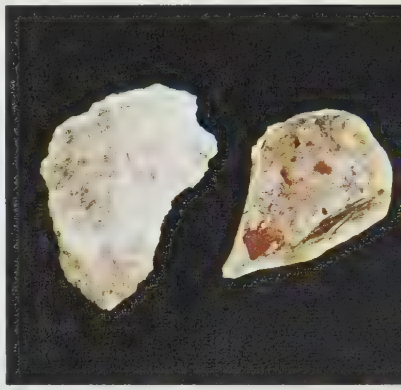


Figure 5-8 Both marble and quartzite have a uniform crystalline texture, something like fine granulated sugar. Neither can be split along predictable planes. (*Left*) marble; (*right*) quartzite.

Study Guide

1. Explain what a petrologist means by the term *metamorphism.*
2. Name the physical conditions that may cause metamorphism to occur.
3. Give two methods for classifying metamorphic rocks.
4. Name three metamorphic rocks and the type of rock from which each was derived.
5. Describe the differences between foliated and nonfoliated metamorphic rocks.

5-11 HOW SEDIMENTS ARE CEMENTED TO FORM ROCKS

It is not easy to see how sediments in the sea turn into rocks. Even geologists are not quite sure how it happens, but they

To make concrete, mix sand and cement, and add water. The mixture will slowly harden, and the result is a man-made rock. The sand and cement represent the sediment, and the water represents the sea.

do have some ideas about it. You can make an artificial rock that is very much like a sedimentary rock. We call this artificial sedimentary rock **concrete** (see comment in the margin).

One kind of natural cement found in sedimentary rocks is the calcium carbonate from the shells of animals that live in the sea. These shells dissolve very slowly in seawater. Shell material dissolves more readily in water that contains carbon dioxide than in water that does not contain this gas. When the animal that lives in the shell dies, its body decays. One of the products of decay is carbon dioxide. The shell, the water, and the carbon dioxide combine chemically, forming a natural cement. A sedimentary rock that is eventually formed only of such cement is called **limestone** (see Figure 5-9).

Grind a piece of shell into a powder and sprinkle the powder into water. Blow bubbles into the water through a drinking straw. The cloudiness will disappear. The carbon dioxide of your breath reacts with the water and the shell. If you heat this solution of shell-in-water, the cloudiness will return.

You can prove to yourself how quickly the material in shells will dissolve in water with carbon dioxide by doing the experiment described in the margin. If wet sediments that contain dissolved shells are heated, the dissolved material comes out of solution and cements the sediments together – in this case, calcium carbonate.

What does this tell you about how the material of dissolved shells can cement a rock? Long ago, physicists discovered

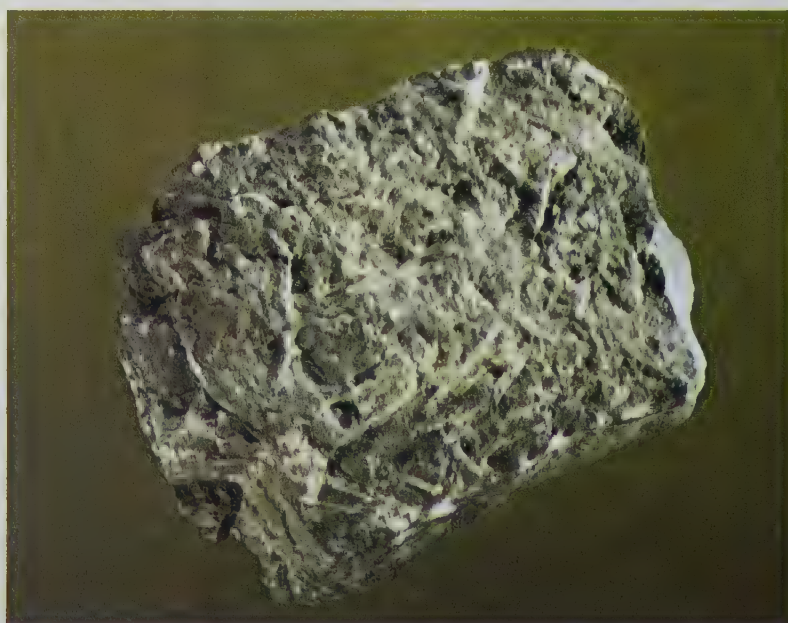


Figure 5-9 Sediments that are cemented with dissolved shell material are said to have *limy cement*. The lime used for making plaster is either from limestone or from ground-up shells.

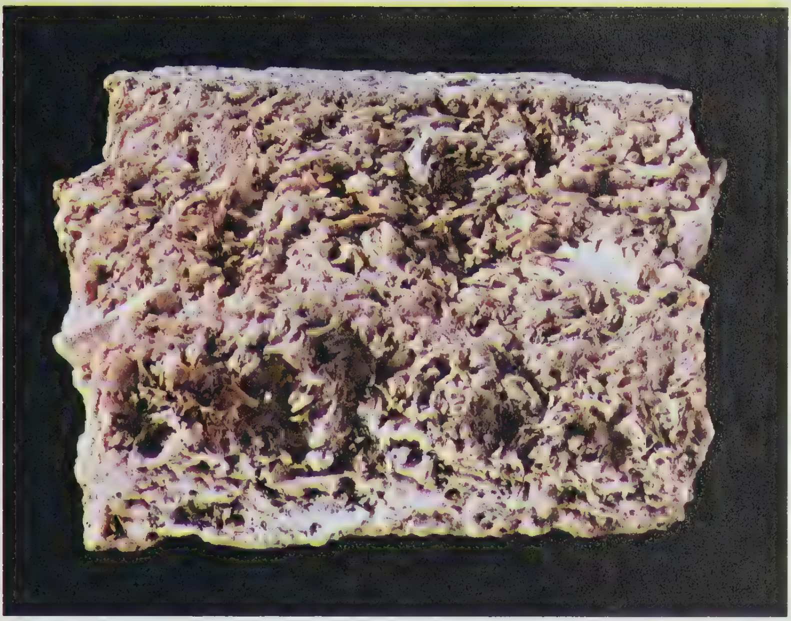


Figure 5-10 In some places, such as parts of Florida, a limestone is formed from pieces of shell. Many of the beaches in Florida are composed of shell fragments.

that when you squeeze things, they get hot. When you pump air into a bicycle tire, you squeeze the air and its gets hot. When you pound a nail with a hammer, you squeeze the nail and it gets hot. When sediments are piled to great thickness on the sea bottom, they are squeezed. For example, where the Mississippi River flows into the Gulf of Mexico, the sediments may be almost five miles thick. These squeezed layers of sediments get warm enough to cause the dissolved shell material to change into cement.

In most limestone, there are more nonshell particles than shells. Sometimes, however, only a small portion of the shells buried in sediments are dissolved. When this happens, the remaining shells also become part of the limestone. Figure 5-10 shows some of this kind of limestone, called **coquina.**

coquina (koh KEE nuh).

There are several other materials that bind particles together in sedimentary rocks. The most common of these is **silica**, which is quartz. Silica can cement sand into sandstone (turn back to Figure 5-3). Most sand is made of small particles of quartz, which is a very hard mineral. Another characteristic of quartz is that it does not react as readily as do most other minerals. For example, quartz dissolves very slowly in

Silica is another name for silicon dioxide, the chemical makeup of the mineral quartz.

Figure 5-11 By the process of metamorphism, the remains of plants are changed to a type of metamorphic rock—coal.

water. It dissolves a little better in salt water than in pure water. Therefore, after a very long time, enough silica dissolves in seawater to cement grains of sand together, forming sandstone. In the ocean, some of the dissolved silica comes from the shells, called **tests**, of microscopic animals that live in the sea.

Some sedimentary rocks are cemented together with compounds of iron found in many igneous rocks. When these igneous rocks decompose, the minerals enter the sea as part of the sediments. Salt water dissolves the minerals and helps to release the iron. The dissolved iron then unites with dissolved silica, forming a very hard cement.

5-12 ORGANIC REMAINS IN ROCKS

Coal deposits, found between layers of sedimentary rocks, are the fossils of ancient forms of trees (see Figure 5-11). We believe petroleum comes from the remains of living things that were trapped in mud or sand that was later turned into shale or sandstone. How would these facts and theories help a geologist looking for oil? In the next chapter you will see how fossils are used to establish the relative ages of sedimentary rocks.

5-13 THE SURFACE ROCKS OF NORTH AMERICA

Any of the three major types of rocks we have discussed may be found on the surface of the earth. In some places these

uppermost rocks are buried under soil that has been formed from them. In other places they are covered by sediments that were strewn over them by streams, glaciers, or ancient oceans. More than half the United States has sedimentary rocks on its surface, although they may be covered by soil. Most areas of sedimentary rock were once underwater. Figure 5-12 shows the various kinds of surface rocks in North America.

The surface of the rest of the United States is made up of crystalline rocks. Much of the eastern part of the United States consists of metamorphic rocks, and considerable areas in the western part of the United States consist of igneous rocks. Large areas of Canada's surface rock are metamorphic, covered by a very thin layer of soil. In the central part of Canada, as in the United States, there are very thick layers of sedimentary rocks directly under the soil.

In many places where the surface rocks are crystalline, there is good evidence that sedimentary rocks once covered the present surface rocks. The layers of sedimentary rocks that have disappeared were reduced to debris and washed back into the sea, forming new sedimentary rocks.

Figure 5-12 The surface rocks of North America

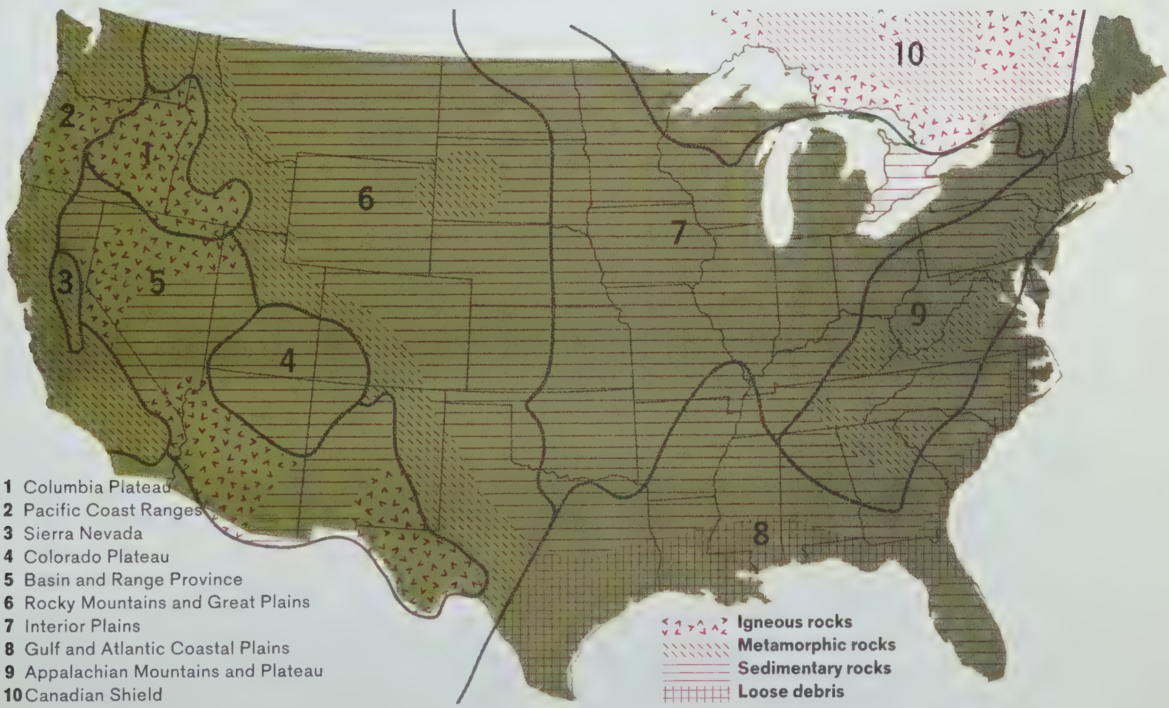


Figure 5-13 The rock cycle shows how igneous, sedimentary, and metamorphic rock are related. When the earth was first formed, what was the only kind of rock?

It is probable that in some cases the heat deep in the earth was so intense that metamorphic rocks melted, then cooled, forming new igneous rocks. In that way, what originally had been part of an igneous rock passed through a full cycle and again became part of an igneous rock. This cycle is called the **rock cycle** and is illustrated in Figure 5-13. Hutton suspected that such a cycle might exist. It has remained for modern geochemists to explain how it happens.

Study Guide

1. Explain why concrete is a man-made sedimentary rock.
2. Name three cementing materials found in seawater.
3. Name the materials bound together by the cementing materials in seawater.

4. Give a definition of limestone.
5. Where are fossils formed?

SUMMARY

Rocks are classified first by the way they have been produced, second by the minerals that compose them, and finally by their texture. Igneous rocks are crystalline and are produced from molten material that has cooled and hardened. Sedimentary rocks are produced in water, usually in the ocean, by the cementing of sediments. Metamorphic rocks are crystalline rocks that have been produced from either igneous rocks or sedimentary rocks. A variety of agents may cause metamorphic rocks to form: heat, pressure, and chemical change. Igneous rocks pass through a fluid state; metamorphic rocks do not.

REVIEW AND DISCUSSION QUESTIONS

1. What kind of rock makes up the basement rock found beneath all sedimentary rocks?
2. Why did Werner call sedimentary rocks "secondary"?
3. How is each of the following carried by a moving stream: mud, sand, pebbles?
4. What is the distinction between debris and sediment?
5. How does moving water sort the material it carries?
6. Some places along the seashore have sandy beaches, others have stony beaches, and still others have shores that are muddy. What causes the differences?
7. Explain how conglomerates are formed.
8. Explain how sediments are formed.
9. How are igneous rocks formed?
10. How could the intrusion of layers of igneous rocks not follow the principle of superposition?
11. In what ways are granite and rhyolite similar? How do they differ? What causes the difference?
12. How can a porphyry be recognized?
13. Why does the shell of an animal that lives in the sea dissolve more rapidly after the death of the animal than during its lifetime?
14. How are coal deposits developed in the crust of the earth?
15. Why would a geologist looking for oil be particularly interested in sandstone and shale?

CHAPTER 6

THE FOSSIL RECORD

We have seen how both Werner and Hutton reasoned that the igneous (primary) rocks were older than the sedimentary (secondary) rocks. Using the principle of superposition, early geologists reasoned that horizontal layers of sedimentary rocks at the top of a hill must be younger than those at the bottom of the hill.

Neither Werner nor Hutton knew how to compare the actual ages of two different sedimentary rocks, nor did they know how to relate two geographically separated sequences of sedimentary rocks. The problem essentially was this: How do you recognize that two rock layers found in different places are the same age?

6-1 SMITH, THE FOSSIL COLLECTOR

William Smith was born in England in 1769. When he finished his studies, he became a surveyor and helped make maps of great farms and mines. While doing this, he collected fossils. Smith lived at the beginning of the industrial revolution, when large amounts of coal had to be mined and delivered to an increasing number of factories. To do this, canals were dug for transporting coal barges across the country. Very soon, Smith was surveying for these man-made rivers. Where the canals cut through rocks and hills, he had a chance to collect more fossils (see Figure 6-2).

6-2 WHAT SMITH LEARNED FROM HIS FOSSILS

Smith's knowledge of fossils and of the rocks that contained them grew with the years. Slowly he began to recognize that certain kinds of sedimentary rocks contain distinct kinds of fossils. He began to match fossils from one part of Britain with those from other parts. He discovered that he could recognize a particular layer of rock, wherever he found it, by the kinds of fossils it contained.

A 50-million-year-old fossil of *mene rhombeus*. It is an ancient relative of the modern pompano.

Figure 6-1 William Smith (English, 1769–1839). When William Smith was eight years old, his father died and he went to live with his uncle, a farmer. The uncle objected to the boy's hobby of collecting fossils, believing such an activity was a waste of time. Little did he realize that it would make the boy well known, not only in England but wherever geology is studied today.

In some cases, a particular organism lived for only a short time in the earth's history. Remember, "a short time" in the life of the earth may mean millions of years. Fossils of these organisms will be found only in the sedimentary rocks formed during the time in which they lived. A fossil of this type is called an **index fossil**. Paleontologists use an index fossil to estimate the age of a sedimentary rock anywhere it is found in the world. A type of fossil that is found in many different layers of rock usually does not make a good index fossil. Why?

The discovery of the relationship between fossils and the rocks in which they are found was an important one. It enabled geolgists to determine the age of a particular layer of sedimentary rock anywhere it was found. This was something neither Werner nor Hutton knew how to do.

Study Guide

1. Where are the younger rocks of a sequence often found?
2. How did Smith's hobby help him to become famous?
3. In your own words, explain what a fossil is.
4. Explain why fossils are important to geologists.
5. What is an index fossil?

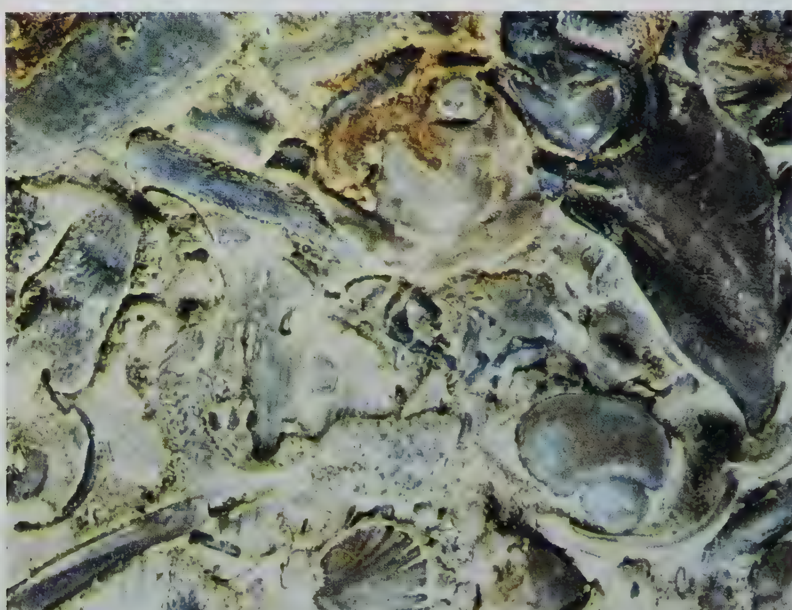


Figure 6-2 Fossils from the Ordovician Period. The fossiliferous limestone contains brachiopods, bryozoans, and trilobite fragments.

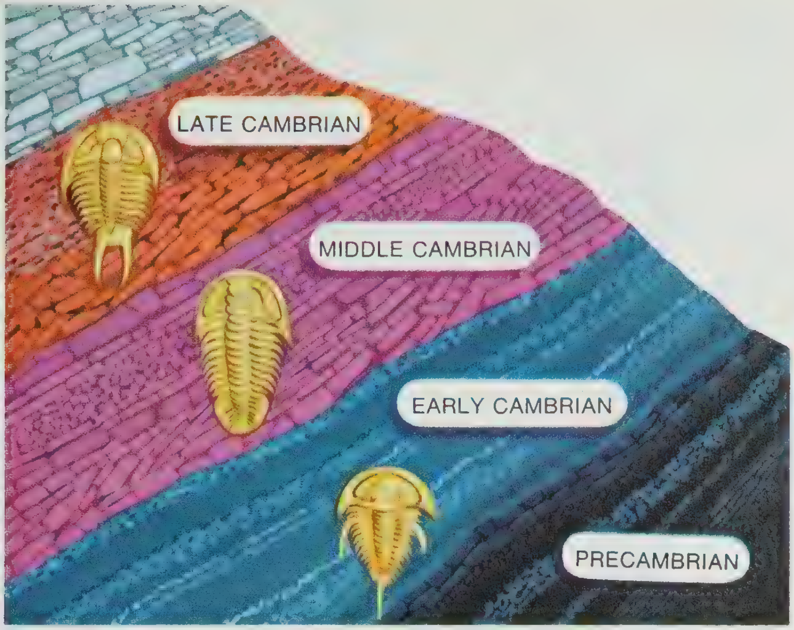


Figure 6-3 A fossil sequence in a series of Cambrian rocks, which enabled paleontologists to estimate the age of the rocks

6-3 THE GEOLOGIC COLUMN

Wherever Smith worked, he made diagrams of the sequence of the rocks and of the fossils he found in them. From his records, he made a kind of calendar. This was not a calendar of days, months, and years, but a calendar of older and younger fossils.

Smith combined information about rocks and fossils from many places—stone quarries, mines, and places where canals and roads cut through sedimentary rocks. When he finished, he had a long sequence of sedimentary rocks and the fossils found in them.

Smith's calendar was arranged so that at the top of the list were the youngest rocks and fossils, and at the bottom, the oldest. He called the list a **geologic column**. It was similar to a calendar in that it was an orderly time sequence. He sent copies of his geologic column to many other geologists. They saw how useful it was and built geologic columns for the regions they were studying.

6-4 BUILDING A GEOLOGIC COLUMN

In Figure 6-4 you will see how a geologic column is constructed. At the left are cross sections of three hills, showing

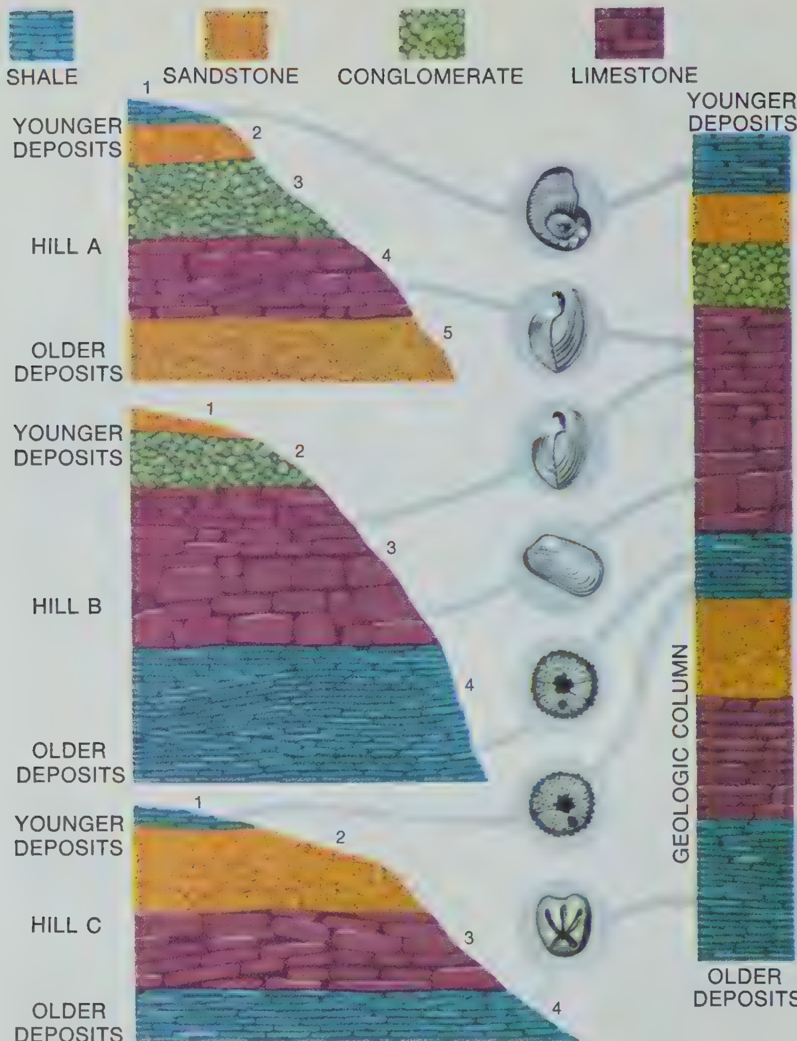


Figure 6-4 Notice that fossils are not found in every stratum. Usually, limestones and shales contain many fossils. Fossils are very rare in conglomerates, and when found they are often badly broken. Try to explain why this is so.

strata (STRAY tuh); Latin: *stratus*, to spread out.

the various **strata**, or layers, of rocks in each hill. Alongside each stratum is a diagram of the principal kind of fossil found there.

Hill *A* contains the youngest rocks. Hill *C*, at the bottom, contains the oldest rocks. The bottom stratum in Hill *C* is the oldest rock type found in all three hills.

The shale at the top of Hill *A* contains a large, curled fossil shell. Below it is a sandstone in which no fossils were found. Beneath the sandstone is a stratum of conglomerate, and below that is a fossil-bearing limestone. The bottom rock stratum in this hill is a sandstone.

Now look at the diagram of Hill *B*. Notice that the top three strata repeat the same sequence of rock found in Strata *A*-2, *A*-3, and *A*-4, in Hill *A*. Notice also that the limestone Strata *A*-4, in Hill *A*, and *B*-3, in Hill *B*, contain the same kind of fossil shell, which can be used as an index fossil. Because of this, we correlate these two strata. This means that we consider them to be the same age.

In a similar way, the various strata in Hill *B* are correlated with those in Hill *C*. When all the information from the three hills is put together, we have the geologic column seen at the right side of Figure 6-4. From this we can develop the geologic history of the region represented by the three hills. Other geologists can use the same column to find the relative ages of strata in other parts of the world.

There is an unsolved problem in this example. Where do we place the sandstone Stratum *A*-5? Since limestones *A*-4 and *B*-3 appear to be the same age, sandstone *A*-5, which is older than limestone *A*-4, would have to be older and thus below limestone *B*-3. But there are no sandstones deep down in Hill *B*. There is one near the top of Hill *C*. Perhaps sandstones *A*-5 and *C*-2 are about the same age. However, we cannot be certain that this is true. If there were fossils in these sandstones, that would help solve the problem.

Notice that the geologist who studied Hill *A* used an irregular line between *A*-4 and *A*-5. This means that he thought the limestone had been laid down on a sandstone that had previously been partly worn away. An unknown amount of rock from the top of the sequence below *A*-4 was removed before the limestone layer was formed. Let us see what may have happened.

6-5 SEDIMENTATION INTERRUPTED

How could sandstone *A*-5 have been eroded before limestone *A*-4 was deposited? The best explanation for such a condition is that after the sandstone had formed, it was uplifted out of the sea and worn away by streams. Then the land sank beneath the sea again, and the material that formed the limestone was deposited on the irregular surface. Thus, the sediments that formed the rocks in Hill *A* were not laid down continuously, one upon the other. The period of sedimentation was interrupted. There may have been other layers between *A*-4 and *A*-5 that also were removed.

Geologists call such a situation an **unconformity**. It means, in this case, that an unknown period of time elapsed between

the times the sediments for sandstone *A*-5 and limestone *A*-4 were deposited. The best we can say is that *A*-5 and *C*-2 may be the same age, but such a statement is only a guess. An unconformity is shown in Figure 6-5.

6-6 HOW FOSSILS ARE FORMED

There is no single, simple answer to the question, How are fossils formed? In all cases, the remains of a plant or an animal are buried in sediments. Then any of several things may happen. In the case of recent fossil shells, after the soft tissue of the animal has decayed and sediments have filled all the cavities, the actual remains have been preserved practically unchanged.

Sometimes, after the soft parts of the animal have decayed, the hard parts become buried and sediments harden around them. Then the hard parts either decay or are removed through chemical action. This removal leaves a **mold** of the original hard parts. A mold is a second kind of fossil.

Water containing dissolved silica, calcium carbonate, or some other mineral may seep into the mold, and the minerals may be deposited there when the water evaporates. Such an event will produce a **cast** of the original hard parts. This is a third kind of fossil.

A common kind of plant fossil is petrified wood. This is a good example of a cast fossil. When the original piece of

Figure 6-5 An example of an unconformity. The sandstone underlying the layers of metamorphic rock has been eroded, causing the two layers of metamorphic rock to be adjacent.

Figure 6-6 The fossil shells, worm trails, and petrified wood are examples of cast fossils. The carbon leaf print and the insect in amber are preserved under different conditions.

wood becomes buried, mineral-bearing water fills the open spaces inside the cell walls of the wood. Then the cells become filled with silica or some other mineral. Slowly the woody cell walls decay, and the spaces that are left also become filled with a mineral. When either animal or plant material is wholly replaced by a mineral, the fossil is a stony cast of the original. Figure 6-6 shows some of the fossil types we have just discussed.

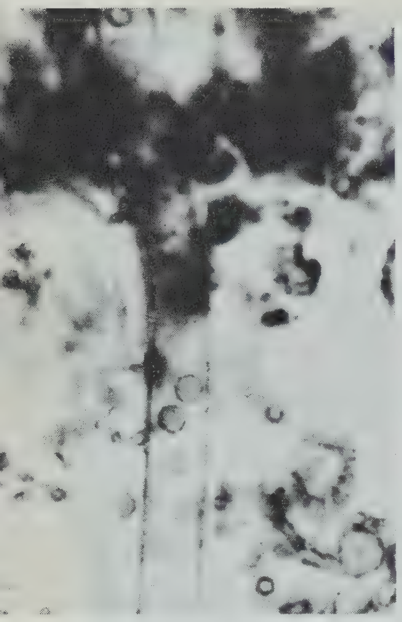


Figure 6-7 This algae filament, found in the Gunflint chert in Canada, is an example of a microfossil. Its estimated age is 2,000 million years.

Plant material that is buried in mud containing little or no oxygen decays only partially, and much of the carbon from the cellulose of the plant remains. This kind of fossil is a **carbon print** of leaves or stems. Under similar conditions, carbon prints of soft animal tissues are formed. Some plant saps, when buried in sediments, harden and become a substance we call **amber**. Insects that had been trapped in the sticky plant sap are sometimes found in amber.

6-7 VERY SMALL FOSSILS

Perhaps the most interesting fossils are **microfossils** — fossils so small that you rarely notice them in rocks. Some microfossils are shown in Figure 6-7. These are the remains of microscopic organisms that had hard parts. Among this kind of fossil are the tests, or shells, of single-celled organisms called **protists**. The ooze that forms at the bottom of the deepest parts of the sea is often composed largely of tests.

protists [PROHT usts). Members of the biological kingdom that includes the simple animals called protozoans and the simple plants called algae and fungi.

Microfossils are difficult to study. Thus far, we have discovered ways of extracting them from shales and certain limestones. For other kinds of rocks it is necessary to make very thin, polished chips of the rocks and study these under the microscope (see note in margin).

A little chip of the rock is ground so thin that light will pass through it. The thin sliver of rock is then mounted on a microscope slide and carefully examined. Not all such slides show fossils.

Study Guide

1. What is the name of a rock formation in which one or more layers in a geologic column are missing?
2. How do unconformities occur?
3. Describe how the remains of a plant or an animal may be converted to a mold fossil.
4. Explain why microfossils are so difficult to study.

6-8 THE KIND OF ROCK IN WHICH FOSSILS ARE FOUND

Fossils are found only in sedimentary rocks. The conditions under which igneous and metamorphic rocks are formed prevent the preservation of fossils. Think about those conditions, and you will see why this is so.

It is probable that fossils occur in all kinds of sedimentary rocks, but this does not mean that we can study them in all such rocks. There are good reasons for this. The sediments richest in fossils are those deposited in shallow seas, where there is an abundance of marine life and plenty of sediments.

In some shallow parts of the sea, however, the action of the water is violent. Any shells that lie on the sea bottom where

waves can pick them up are tossed around and ground into small fragments. The rocks that later form from such sediments, usually sandstone or a conglomerate, do not contain large, whole fossils. They may contain some microfossils, but these are very difficult to extract and study.

In places where the water is stagnant, there is not enough oxygen dissolved in the water to support much life. Few fossils are formed in sediments deposited under such conditions. Deep-sea sediments are composed mainly of microfossils. The deep parts of the oceans contain little life as compared with the shallow parts. This is so because there is little food and light available. Thus, there are few recognizable remains of large animals preserved in deep-sea sediments.

Figure 6-8 Animal skeletons, such as this one of a bison, sometimes are uncovered by erosion of clayey alluvium.

Sedimentary rocks that are formed from deposits made in lake beds sometimes contain the fossils of land animals and plants. Throughout the past 350 million years, a great variety of animals have roamed the continents. What we know about these we have learned from fossils such as those shown in Figure 6-8.

When an animal dies on the land, usually scavengers soon eat it. However, the body of an animal that has drowned in a river sometimes becomes buried in mud or sand. Then there is a good chance that the bones will become fossils. For this to happen, the sediments in which the bones are buried must not be disturbed by violent earth movements or stream action. Also, microorganisms that decay bone must be absent. Such conditions are not common; that is why we find land fossils so infrequently.

One of the most interesting fossil finds took place right in the center of what is now Los Angeles, California. Figure 6-9

Figure 6-9 Thousands of fossil bones of saber-toothed tigers, buzzards, and huge bear-like animals that lived about 1 million years ago have been found at the La Brea tar pits. Some of their bones are on display there today still in place in the tar.

shows a large lake of tar that formed from a deposit of petroleum residue that leaked to the surface millions of years ago. Animals that tried to walk out into this lake were caught in the soft, tarry material. The animals caught in the tar attracted carnivores and scavengers. These, too, were caught in the tar.

Study Guide

1. In what kind of rock are fossils most frequently found? Why?
2. Describe the best conditions for the formation of fossils.
3. How does the activity of the sea affect the chances that animal remains may be converted to fossils?
4. Explain why the fossil record of past life is incomplete.

6-9 THE EARLIEST KNOWN FOSSILS

In the oldest known sedimentary rocks, there are very few fossils. At the time these rocks were still loose sediments, there were probably no organisms containing hard parts that could be preserved. Seldom do we find fossils of soft animals or plants. A few carbon-print fossils of such soft animals as jellyfish have been found, but that kind of fossil is extremely rare.

We are just learning how to recognize and extract fossils in the oldest sedimentary rocks. The index fossils that have been used to build a geologic column are all large enough to be easily seen. The only fossils discovered in the oldest sedimentary rocks are microfossils.

In the early 1960's some very old fossils were discovered in rocks in the northern Great Lakes region, where there is a peculiar sedimentary rock called **chert**. Geologists believe chert is formed from a jellylike silica that hardens into a rock. This fossil-bearing chert is called the Gunflint chert and was probably in the jellylike condition almost 2 billion years ago. At that time, organisms resembling bacteria were trapped in the jelly (see Figure 6-7). A little higher up in the same rock formation, larger fossils were found. These appear to be fossil algae, the sort of green plant that forms pond scum.

6-10 WHAT FOSSILS HAVE TAUGHT US ABOUT LIFE

The oldest rocks from Great Britain that contain easily seen fossils are found in Wales. These sedimentary rocks are called **Cambrian**. For a long time it was thought there were no fossils in rocks formed earlier than Cambrian time. Now we know that the fossils of algae from the Gunflint chert are more than four times as old as Cambrian fossils.

Cambrian (KAM bree un); Latin: Cambria, Wales.

Figure 6-10 Charles Darwin (English, 1809–1882). During his 5-year, round-the-world voyage on a British ship, H.M.S. *Beagle*, Darwin formulated his theory of evolution by natural selection.

It is interesting that the oldest fossils that have been found are of plants and animals that lived in the water. If there were terrestrial plants and animals at that time, we have not yet found their fossils. One reason for the lack of success in finding very ancient land fossils is that few rocks formed from ancient land sediments have been found. Almost all the most ancient sedimentary rocks are of marine origin.

Geologists have found records of only water-dwelling life in the earliest fossil-bearing rocks. Therefore, they believe that life must have originated in water. **Precambrian** fossils are related to the present-day single-celled plants and animals we call protists. The easily seen fossils of Cambrian time represent a variety of plants and animals composed of many cells (see note in margin).

This does not mean that there were no protists in Cambrian time. They have existed in water ever since the time of the earliest fossils, 3 billion years ago. Biologists believe the complex and large plants and animals of the Cambrian seas developed from the simple and small plants and animals of Precambrian time.

William Smith noted that fossils in the upper, or younger, rocks were similar to, but not the same as, the fossils in the lower, or older, rocks. Smith was able to see how the earlier fossil types had developed by small changes into later fossil types. These small changes that he observed in ancient life lend support to the idea of evolution among living things.

Much of Charles Darwin's theory of evolution is based on the fossil records of change among animals and plants. Beginning about 1750, several naturalists suggested that over a long period of time plants and animals have changed, or **evolved**, from kinds that no longer live to those we know today.

evolution; Latin: *evolutio*, act of unrolling.

According to the **theory of evolution**, living things have become adapted to changing environmental conditions through natural selection. **Natural selection** is based on the occurrence of differences, or variations, between offspring and their parents. All offspring of parents that reproduce sexually are different from either parent. Also, variations between offspring and parent may occur because of mutations.

A **mutation** is a change that occurs in the chromosomes and genes of an organism. If this change occurs in a sperm or an egg cell, it may show up in the offspring. This change could be so slight as to be unnoticeable. However, the change may give the organism a slight advantage in the struggle for survival (see note in margin).

This organism will have a greater chance to reproduce offspring that will, in turn, inherit the change. Those organisms that do not have the slight advantage may not be able to compete successfully with those that do. Eventually, the unchanged organisms may become extinct.

Over periods of time measured in millions of years, the effect of many small changes results in organisms so different from the original that they can be called a new **species**. In other words, a new species has evolved from a similar but different ancestor.

6-11 LAND LIFE APPEARS

When sedimentary rocks that are about half as old as Cambrian rocks are examined, we find a most interesting thing. These rocks contain marine *and* terrestrial fossils. This early land life was quite different from that found today.

There are some living species of plants and animals that are closely related to the first ancient land dwellers. For example, frogs, salamanders, scorpions, and spiders are among the animals (see Figure 6-11). And scouring rush is one of the plants that are the closest relatives of the earliest

Figure 6-11 Giant amphibians, such as this fossil, and the salamander probably have a common ancestor.

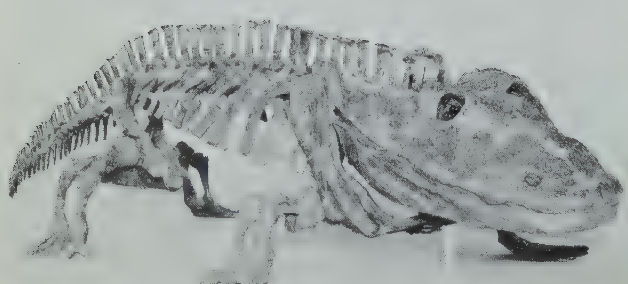


Figure 6-12 Australopithecus may be the earliest member of man's family. The first fossil of this early man was found by Raymond Dart in 1924. Anthropologists date this ancestor of man back about 2 million years.

forms of land life. Most modern animals and plants are not like the ones that first appeared, but they are distantly related to them. Biologists believe all the modern forms evolved from ancient ones.

The earliest fossils of most of the kinds of plants we see about us today come from sedimentary rocks about 150 million years old. The fossils of early mammals are also found in rocks of about the same age. This is evidence that mammals and modern plants appeared on earth at about the same time. The first mammals were about the size of mice. The period of rapid development among the mammals is even more recent, beginning about 60 million years ago. The early ancestors of modern horses were about the size of a fox terrier.

Sixty million years ago, there was nothing living that looked anything like man. We are really newcomers to the earth. The oldest manlike fossils, which have been found in Africa, are only about 2 million years old (see Figure 6-12). The oldest fossil evidence of modern man is probably no more than 100,000 years old—which is geologically very young. Remember, Cambrian rocks are about 550 million years old.

Figure 6-13 The coelacanth is a living link to ancient life forms. This fish formerly was believed to have disappeared 70 million years ago.

As geologists and paleontologists continue to find fossils, the record of past life will become more complete. At present the record is incomplete (see Figure 6-13). We do have a fairly good idea about the general path of evolution, but in very few cases do we have much knowledge of details.

Geologists of the nineteenth century learned more and more about fossils and the use of the geologic column. It then became necessary to give names to parts of the geologic column. Smith did not have these names to use. They were devised by later geologists. Let us next turn to the story of the naming of the periods during which sedimentary rocks were formed.

Study Guide

1. If one set of fossils appears above another set of fossils in the same rock formation, which set is usually older? Why?
2. Explain what paleontologists mean by the term *Precambrian.*
3. What evidence is there that the rate of evolution among the early mammals was faster than it was among the early reptiles?
4. State a possible reason why the earliest fossils were marine forms of life.

SUMMARY

The studies of William Smith have been important to many branches of science. He showed us how to recognize that two different rock layers are about the same age, based on the fossils they contain. A fossil that can be used by a geologist to find the age of a stratum relative to other rock strata is called an index fossil. The geologic column, developed by Smith, is a record of the sequence of many layers of sedimentary rocks.

Geologists know that there are three major conditions in which the remains of a plant or an animal can be found. Recently, microfossils have been identified. They have been found to be as much as 3 billion years old. Smith's interpretation of fossils became the basis for much of the evidence that supports Darwin's theory of evolution.

REVIEW AND DISCUSSION QUESTIONS

1. Explain why William Smith's profession was helpful to his study of fossils.
2. How do the two types of fossils found in Gunflint chert differ from each other?
3. William Smith noted that different kinds of fossils appear in rocks of different ages. Explain why this is evidence for the theory of evolution.
4. Explain why biologists believe the fossil record of the past is incomplete.
5. The majority of fossils in rocks formed from sea sediments once lived in relatively shallow water. Today we find sediments of the kinds we believe become conglomerates, sandstones, limestones, and shales accumulating in relatively shallow seas. Would you expect rocks formed from sea deposits of the same age to contain exactly the same fossils? Why, or why not?
6. In what ways have geologists given biologists information to support the theory that living things gradually change and become more complex?
7. How do geologists decide whether two rock strata found in different places are the same age?
8. When studied under a microscope, some pieces of fossilized wood clearly show every cell, and others do not show cellular structure at all. How would you explain this?
9. Why are fossils not found in metamorphic rocks that are made from sedimentary rocks?
10. It is probable that all sedimentary rocks that formed from either marine or freshwater deposits contain microfossils. If this is the case, why have so few microfossils been studied?
11. The Morrison shale formation, rich in fossils of large animals, is found throughout the Rocky Mountain region. Geologists believe it represents, in most cases, the hardened sediments of river deposits. Why are such sediments particularly good for the formation and preservation of fossils of land animals?
12. Examine the geologic column for your state. Write a brief account about the geologic time when your state was invaded by the ocean.

CHAPTER 7

NAMES FOR THE AGES OF ROCKS

William Smith's geologic column attracted the interest of geologists in Europe. As a result of his discoveries, two other Englishmen became interested in the geologic column. One of them was Adam Sedgwick, a minister who taught at a college in Cambridge. The other was Roderick Murchison, a retired army officer. Their common interest in rocks and fossils made them friends.

One summer, in 1835, Sedgwick and Murchison decided to collect fossils in Wales. Sedgwick went to the northern part of Wales and Murchison to the southern part. They found that many of the fossils in Wales were different from those in central England. It became difficult to describe to other collectors precisely what kinds of rocks and fossils were being discovered. What they needed were special names for the two sequences of rocks they were studying.

7-1 WHY NAMES ARE NEEDED

Murchison made up a name for his rocks. He had found them in the area that had been inhabited by the ancient British tribe called the Silures. So he called his rocks *Silurian*. He urged his friend Sedgwick to call his rocks *Cambrian* from the ancient name for Wales. We use these names today for rocks all over the world that are the same age as the two sets found in Wales.

Studies of these two sequences of rocks and fossils revealed that the fossils at the top of the Cambrian sequence were just about the same as those at the bottom of the Silurian sequence. This suggested that the Cambrian rocks were the older of the two. At about the same time, other sequences

The chalk cliffs of Dover overlooking the English Channel near Folkstone, England

rich in fossils were being found in England and other parts of Europe. None of these fossil-rich sequences contained fossils older than the ones found in Cambrian rocks. As rocks and fossils in other parts of the world were studied, it was discovered that the same thing held true. Cambrian rocks are the oldest rocks containing abundant fossils.

As geologists studied the rocks and fossils in various parts of the world, many other sequences were found. Each of these was given a name—usually derived from the place in which the rock was found. In Chapter 8 you will find a list of these names.

It took geologists many years to place their many local rock sequences into a single major sequence. Slowly, a geologic column that contains information from all over the world was assembled. Geologists did this by carefully comparing fossils and noting how they and the rocks containing them fit into the sequences of strata described in the previous chapter.

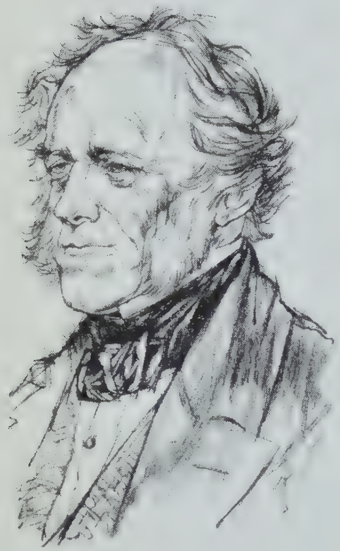


Figure 7-1 Sir Charles Lyell (Scottish, 1797–1875). Although Lyell studied law at Oxford and was admitted to the bar, he was fascinated by geology and gave most of his time to the subject. His investigations led him to the theories of volcanism and the principle of uniformitarianism. He contributed nothing fundamentally new to geology, but he was first to name a number of geologic eras.

7-2 THE NAMES PROPOSED BY LYELL

The man most responsible for the geologic column we use today was a Scotsman named Charles Lyell. He spent most of his life organizing what other geologists had discovered. In 1830 he published the first modern textbook on geology, one that had a great effect on Darwin's thinking about evolution. By 1872 Lyell had developed a geologic column much like the one we use today (see Figure 7-2).

Before Lyell had put together a worldwide geologic column and time scale, other geologists had constructed columns for their parts of the world. The geologists who had built these local columns named the various parts of their column as they wished. As a result, rocks of the same age in various parts of the world were given different names. This made it difficult to compare rocks and fossils from one part of the world with those from another.

What Lyell did was to apply one name to the rocks of the same age from all parts of the world. These names separated rock layers according to their age into major time periods.

7-3 PERIODS AND SYSTEMS

The geologic column contains information about rocks based on the fossils contained in these rocks. To avoid confusion, geologists use such names as Cambrian to designate either a period of time or a rock type that contains a certain kind of

TABLE II.

Showing the Order of Superposition, or Chronological Succession, of the principal Sedimentary Deposits or Groups of Strata in Europe.

This Table is referred to in the Glossary, and includes the Secondary Formations alluded to in this Work, but not described in detail.

Periods and Groups.		Names of the principal Members and general Mineral nature of the Formation.		Some of the Localities where the Formation occurs.
I. Recent Period.		The deposits of this period are for the most part concealed under existing lakes and seas.		
I. Recent Period.	A	Consolidated sandy and gravelly beds (*a*), travertin limestones (*b*), calcareous sandstones with broken shells (*c*), coral limestone, consisting of corals, shells, &c. (*d*)		*a*. Delta of the Rhone. *b*. Tivoli, and other parts of Italy. *c*. Shore of island of Guadaloupe. *d*. Coral reefs in Pacific, &c.
II. Tertiary Period.	B Newer Pliocene.	Marine. *Limestone*, sands, clays, sandstones, conglomerates, marls with gypsum; containing *marine* fossils (*a*).	Freshwater. Sands, clays, sandstones, lignites, &c.; containing *land* and *freshwater* fossils (*b*).	*a*. Sicily, Ischia, Morea? *b*. Colle in Tuscany.
II. Tertiary Period.	C Older Pliocene.	*Subapennine marl, Subapennine yellow sand, English 'crag,'* and other deposits, as in B, containing *marine* fossils (*a*).	Similar deposits to B; containing *land* and *freshwater* fossils (*b*).	*a*. Subapennine formations, Perpignan, Nice, Norfolk and Suffolk. *b*. Near Sienna, &c.
II. Tertiary Period.	D Miocene.	*Faluns of the Loire*, and other deposits of similar mineral composition with B and C, containing *marine* fossils (*a*).	Similar deposits to B and C; containing *land* and *freshwater* fossils (*b*).	*a*. Touraine, Bordeaux, Valley of Bormida, Superga near Turin, Basin of Vienna. *b*. Saucats, twelve miles south of Bordeaux.

Figure 7-2 A page from Lyell's *Priniciples of Geology*, showing part of a geologic column

fossil. When they speak of the *time* that Cambrian fossils were abundant, they use the term **Cambrian Period**. When they speak of the *rocks* that contain Cambrian-age fossils, they use the term **Cambrian System**.

As geologists learned more about fossils, they found that they needed more time periods to hold their fossil findings. It

became necessary to group the periods into larger units. Such a unit is called an **era**. Four eras are now recognized.

7-4 ERAS

How do geologists decide when one era ends and another begins? They separate the eras from each other on the basis of evidence of major geologic changes on the earth.

The oldest sedimentary rocks we have found contain few, if any, fossils. Most of these are microfossils, like the ones described in Section 6-7. Because of the lack of fossils, it is difficult, if not impossible, to classify these rocks into periods. Therefore, all the earliest rocks are usually lumped into one era called the **Precambrian Era.**

Paleozoic (pay lee uh ZOH ik); Greek: *palai*, long ago + *zoe*, life.

Younger than the Precambrian rocks, but still very old, are the rocks that contain an abundance of easily seen marine fossils. These rocks were formed during the era when marine life was dominant. This is called the **Paleozoic Era**. Because of the abundance of fish fossils, this era is commonly known as the **Age of Fishes**.

Mesozoic (meh zuh ZOH ik); Greek: *mesos*, middle + *zoe*, life.

By the close of the Paleozoic Era, there was a large population of reptiles living on the land. The period during which reptiles became the dominant animals on land is called the **Mesozoic Era**, or the **Age of Reptiles.**

Cenozoic (see nuh ZOH ik); Greek: *kainos*, recent + *zoe*, life.

Toward the close of the Mesozoic Era, another kind of land life—mammals—proved to be so successful in competing for survival that they soon became the dominant form of life. Thus, the Mesozoic Era gave way to the **Cenozoic Era**, or the **Age of Mammals**. This is the era in which we are living today. Now let us look at each of the eras in greater detail.

Study Guide

1. Explain why scientists found it necessary to use names for the ages of rocks.
2. Describe how Charles Lyell constructed his geologic column.
3. Into what larger units are periods grouped?

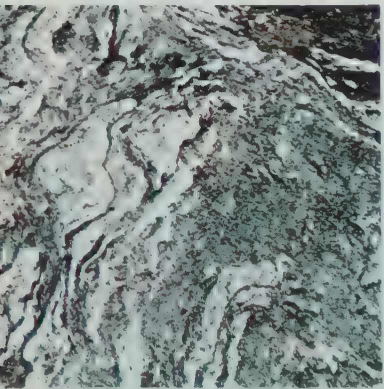


Figure 7-3 Schist, a metamorphic rock, was folded under pressure. Folding and heating destroy any evidence of fossils.

7-5 THE PRECAMBRIAN ERA

The study of the Precambrian Era has been handicapped for two reasons. It occurred so long ago that many of the sediments have since metamorphosed. Most Precambrian rocks are either igneous or metamorphic. The heating and bending of the many sedimentary rocks of the Precambrian Era have destroyed any evidence of fossils (see Figure 7-3).

The other handicap is that, at least in early Precambrian time, life in the seas was composed of only single-celled or very small plants and animals. Such life produces fossils that are difficult to study under the best conditions. Only within the past few years have geologists been successful in studying the fossils of Precambrian time.

The most visible, and therefore the best-known, fossils of the Precambrian Era are great rounded masses of limestone produced by a kind of algae. Such algae are known today, living in lakes and in the oceans, where they form similar structures (see Figure 7-4). Less easily discovered are the smaller forms of life that do not deposit lime. In Section 6-9 we mentioned microfossils from early Precambrian deposits such as the Gunflint chert. Other kinds of life also must have existed during this early era.

Figure 7-4 These fossils from Saratoga, New York, are probably the best examples dating from the Precambrian Era. They appear as ridges or circles in the limestone.

7-6 THE PALEOZOIC ERA

The earliest period of this era is the Cambrian. It is logical that a system in which there were many fossils would be younger than a system containing almost no fossils. Also, Cambrian rocks are almost always found above Precambrian rocks. Remember the principle of superposition?

By the time the rocks of the Cambrian System were being formed, there was an abundance of easily recognized life in

Figure 7-5 A scene in a Cambrian sea shows life in the Paleozoic Era.

Figure 7-6 These are fossils of trilobites, ancient arthropods. They were the most highly developed creatures of the time and were contemporary with the horseshoe crab, which still exists. Most of the trilobites were from 1 to 4 inches long. At least one kind, however, grew to a length of almost 18 inches.

lichen (LYE kun). A simple plant association of an alga and a fungus (Figure 9-13).

trilobite (TRYE luh byet); Greek: *trilobos*, three-lobed. This refers to the three main body sections of the animal.

brachiopod (BRAY kee uh pod); Latin: *brachium*, arm + Greek: *pod*, foot.

the seas (see Figure 7-5). All the evidence we have today suggests that the land was without life during the Cambrian Period. There may have been plants such as lichens growing on the rocks, but we have no evidence to support this guess.

The most important fossils from the Cambrian Period are the trilobites (see Figure 7-6). These curious animals have long been extinct but have become the index fossil for the Cambrian Period and the early Paleozoic Era. Fossils of trilobites are found mostly in the rocks of the early half of the Paleozoic Era.

Other kinds of fossils, such as brachiopods (see Figure 7-7), are also found in Cambrian rocks. Worm burrows and cal-

Figure 7-7 Brachiopods are animals protected by a shell like that of a modern scallop. The fossil cast and mold date back to the Devonian Period. What other modern relatives of the brachiopods, besides the scallop, can you think of?

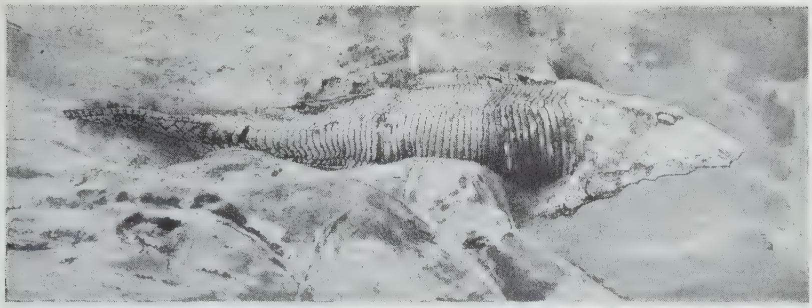


Figure 7-8 The armored ostracoderm was a jawless, bony-plated fish, which populated the Ordovician seas. Modern-day lampreys were contemporary with this fish; they have a sucking mouth instead of jaws.

careous algae, found in the much earlier Precambrian rocks, are also found in Cambrian rocks.

Just above the Cambrian System is a sequence of rocks deposited during the **Ordovician Period**. The rocks of this period contain fossils of groups of marine animals not found in the Cambrian rocks. Most of these are the remains of invertebrates—those animals that have no backbone. During the Ordovician Period, however, a great advance in life occurred. Primitive bony fish evolved (an armor-plated, jawless type), one of which is shown in Figure 7-8. These were the first animals known to have a backbone. There is still no evidence of land life in Ordovician time.

Ordovocian (awr duh VISH un); Latin: *Ordovices*, an acient tribe of northern Wales, where fossils were discovered in 1886.

During the next period of the Paleozoic Era, the **Silurian**, a great event appears to have taken place. Small fragments of fossilized terrestrial plant stems bearing tiny leaves have been found in several Silurian rocks. Also, fossils of ancient animals that appear to be the direct ancestors of scorpions and millipedes have been found in other Silurian rocks. Some paleontologists accept these fossils as evidence of land life.

The **Devonian Period** followed the Silurian. From the fossil record of that period, we see that fish became abundant. Sharks were common. Among them were a number of types whose teeth were adapted to crushing the shells of mollusks and other bottom-living animals. The rise of this kind of shark coincides with the decline of trilobites. What does this suggest to you?

Devonian (dih VOH nee un); from the region of Devonshire, England.

Another kind of fish common during the Devonian Period was probably capable of breathing air. Unlike other fish, these had channels through the roof of the mouth, leading to

the nostrils. These animals were the forerunners of vertebrate life on the land. Indeed, toward the close of the Devonian Period some of the descendants of these early air breathers probably did live on land. After millions of generations, they evolved into amphibians. These are the ancestors of the animals we know today as salamanders, frogs, and toads. For a museum display of the early development of life on land, see Figure 7-9.

During the Devonian Period the land became populated with plants. Devonian forests were fernlike and different from most modern ones. However, among these early trees were the ancestors of the trees of our present forests. Once land plants spread, land animals could multiply in number and kind. Forests supplied abundant food and shelter for them.

Carboniferous (kahr buh NIF uh rus); from carbon, or coal.

The evolution of many new forms of land life characterized the next great period, the **Carboniferous** (see Figure 7-10). Many of the great coal beds of the eastern United States were formed from the forests of the Carboniferous Period.

Reptiles evolved from certain amphibians that had completely deserted the water. Insects became common, and many forms did not look much different from those we see today in our tropical forests. In the seas the trilobites had become almost extinct, but most of the other classes of invertebrates—the brachiopods, mollusks, corals, and others—continued to multiply. Fish were abundant.

Permian (PUR mee un); from Perm, a region in Russia.

The close of the long Paleozoic Era is marked by major geologic changes that took place during the last of its periods, the **Permian** (see Figure 7-11). Mountain ranges, such as the Appalachians, arose from the low-lying continents. Great glaciers covered tens of thousands of square miles of the continents in the Southern Hemisphere. The climate changed almost everywhere. All this had its effect on life, especially life on the land. Reptiles evolved into many different forms. Some became meat-eaters; others continued to feed on plants.

In the forests true conifers developed. The trees began to look more like those that we see today, although truly modern forests had not yet evolved. With new forms of plants, producing different habitats, many new forms of insects evolved—mayflies, dragonflies, and beetles, for instance. In the oceans, change was less drastic but occurred nevertheless. Try to explain why there was less change in the oceans. The Permian was a period of rapid evolution both on the land and in the seas. It ushered in the next major era.

Figure 7-9 Life in the Devonian Period. Notice the fernlike plants. Ferns are a group of plants that bear no flowers.

Figure 7-10 Life in the Carboniferous Period. Animal life on land continued to increase and to evolve during the Carboniferous Period.

Figure 7-11 Life in the Permian Period. Conifers are cone-bearing plants. Pine and spruce are common conifers.

7-7 THE MESOZOIC ERA

In the Mesozoic Era, only three periods are recognized. The first of these is called the **Triassic Period.** The forests of that time began to look like our modern forests. Some of them, probably in the warm, moist areas of the earth, were composed largely of ferns and cycads—curious palmlike plants that are more closely related to pine trees than to palms. In the drier and cooler regions, forests of huge conifers evolved from earlier existing plants. The trees that produced the Petrified Forest of northern Arizona were Triassic conifers.

Triassic (try AS ik); Latin: *trias*, triad. Originally discovered as three related groups of sediment in Germany.

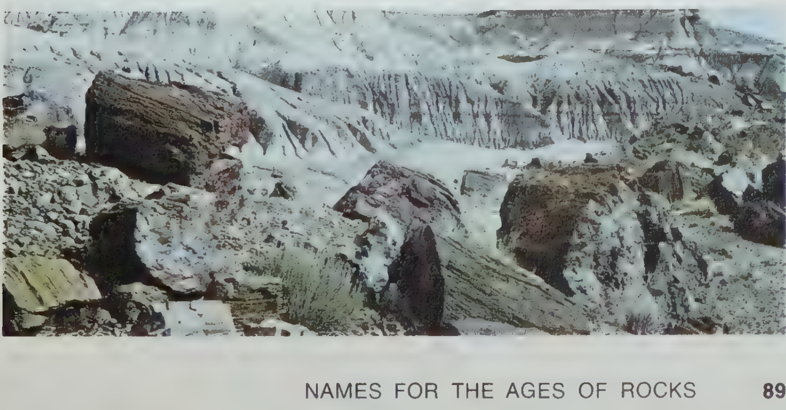


Figure 7-12 Although the trees that grew in the Petrified Forest of Arizona were types of conifers, they did not closely resemble present-day pine trees.

dinosaur (DYE nuh sawr); Greek: *deinos*, terrible + *sauros*, lizard.

Jurassic (juh RAS ik); from the Jura Mountains of France and Switzerland.

Many types of reptiles evolved. One of these was the dinosaur. Other forms of reptiles began to vary in a way that led to the evolution of birds and mammals in a later period. Some of the reptiles returned to the sea, and others began to glide from tree to tree in the forests.

During the **Jurassic Period**, which followed the Triassic, reptiles continued to dominate the land, as suggested in Figure 7-13. Some became quite birdlike, and before the end of the Jurassic Period, a few true birds had evolved. Some types of small reptiles developed into the earliest known mammals. These warm-blooded vertebrate animals were better equipped to compete for survival than were the cold-blooded reptiles.

During the last period of the Mesozoic Era, the **Cretaceous Period**, the land was worn down by erosion and was invaded by the sea. The sediments deposited at that time were often rich in lime from seashells. As a result, the Cretaceous Period takes its name from the Latin word *creta,* which means "chalk," a soft kind of limestone. The famous White Cliffs of Dover, shown at the beginning of this chapter, were formed at that time.

In North America the invading seas flooded about half of what is now dry land. Then, as in the Permian Period, there

Figure 7-13 Life in the Jurassic Period. Mammals and birds whose body temperature remains constant are called warm-blooded. All other forms are called cold-blooded; their body temperature responds to changes of external temperature.

Figure 7-14 Life in the Cenozoic Era. The ancestors of the mammals we know today flourished in the Early Tertiary Period.

followed a long time of mountain building. Both of these great events had a marked effect on land life. Since there was less dry land, there was less living space and plant food available to land animals. Thus, there must have been strenuous competition for food, which worked to the disadvantage of some kinds of animals. The species that were unable to compete successfully, such as the large dinosaurs, became extinct.

As the mountains rose, some areas became cut off from the mild, moist winds from the sea. This changed the climate from one that was generally uniform throughout the year to one with distinct winters and summers. The new conditions of temperature and moisture determined the kinds of plants that could survive.

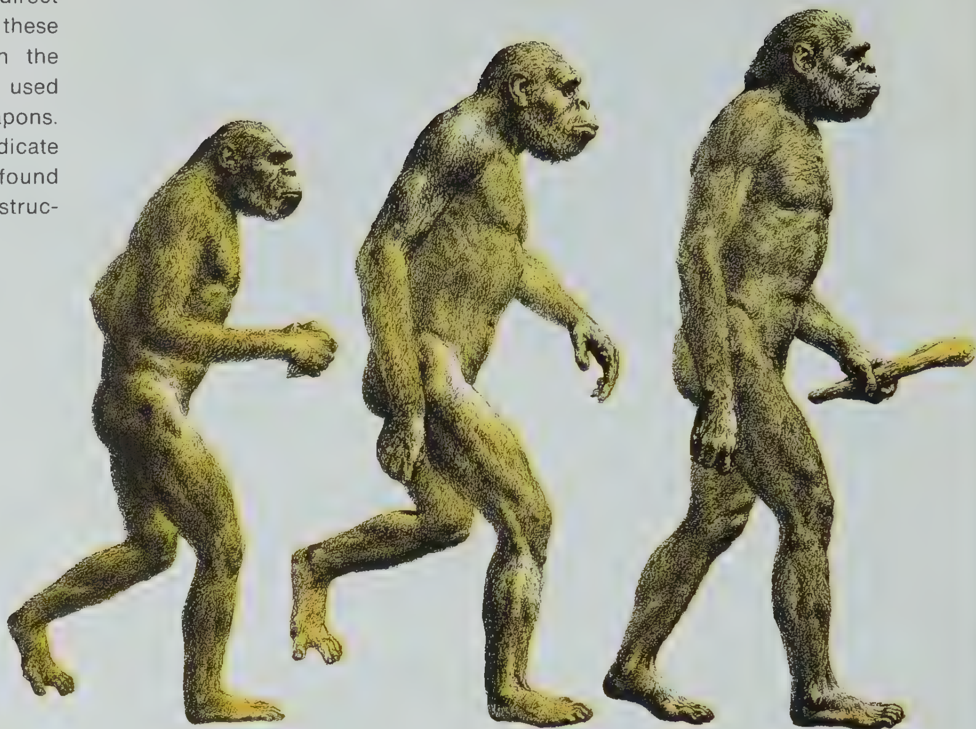
During the Cretaceous Period, modern forms of plants began to form forests and grasslands like those we have today. The change in the kinds of plants also had its effect on animals. Plant-eating animals that could not adapt their feeding habits to the new kinds of plants were at a disadvantage. Their numbers declined and they became extinct.

The fossil record shows that during the latter part of the Cretaceous Period a great many species of animals and plants disappeared. This part of the Cretaceous Period has been called "the time of the great dying." Biologists and geologists think the changes in climate and topography we have just described may have been the reason for this rapid changing of animal and plant life.

7-8 THE CENOZOIC ERA

The rapid evolution of mammals introduced the Cenozoic Era, the one in which we live (see Figure 7-14). There are

Figure 7-15 These figures may represent man's direct ancestors. The earliest of these walked upright, lived on the ground, and may have used stones as tools and weapons. The white highlights indicate the bones that have been found and used in these reconstructions.



AUSTRALOPITHECUS PARANTHROPUS ADVANCED AUSTRALOPITHEC

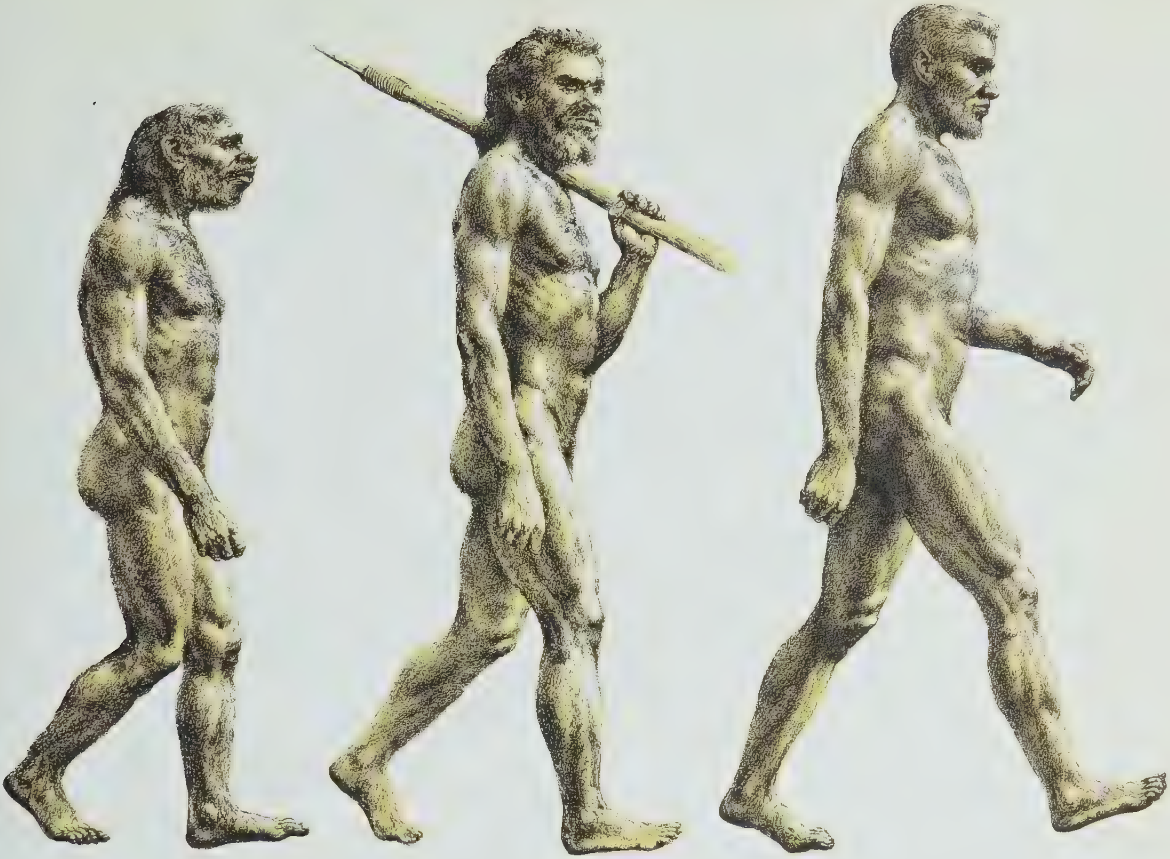
Tertiary (TUR shee ehr ee); Latin: *tertius*, third. Used by Werner in the 1750's, when geologic history was divided into three eras: primary, secondary, and tertiary.

Quaternary (KWAHT ur nehr ee); Latin: *quaterni*, four each. Used because it follows the Tertiary.

Pleistocene (PLY stuh seen); Greek: *pleistos*, most + *-cene*, recent.

two periods in this era, the Tertiary and the Quaternary. During the **Tertiary Period**, mammals evolved rapidly, as if nature were experimenting with the forms they could take. Eventually, only those forms that were the ancestors of modern mammals became dominant. The early evolution of man began about 2 million years ago, during the Tertiary Period, and proceeded rapidly to the present (see Figure 7-15).

The **Quaternary Period** begins with the great Ice Ages of the past million years or so. It has been common practice to divide the Quaternary Period into the **Pleistocene Epoch** and the **Recent Epoch**, the latter beginning only 10,000 years ago. Such a division is based only on the known record of the development of modern man and on a guess that glaciation has ended. The early record of man is far from complete, and glaciation may start again in the future. Therefore, it is probably more reasonable not to divide the Quaternary Period into subdivisions until we have more information.



NEANDERTHAL MAN CRO-MAGNON MAN MODERN MAN

In this very brief review of the history of life and its association with the geologic periods, we have seen that changes took place slowly and in an orderly manner. We have also seen some of the reasons for our artificial division of time into eras and periods.

Determining the age of sedimentary rocks by the fossils they contain depends of course on time, but not time in years. We can say that one rock is older or younger than another. We cannot say exactly how old a rock is. All we can establish is the *relative* ages of the sedimentary rocks.

For a long time, scientists have been trying to find a way to date rocks. This means that they try to assign to each system, or stratum, of rock an *absolute* age in years rather than a relative age. No one way to date all rocks has yet been found. But let us turn our attention in the next chapter to ways that have been developed to determine absolute ages for the earth and its rocks.

Study Guide

1. Name two difficulties in studying the oldest known forms of life.
2. In what environment do we believe the earliest forms of life developed? Explain why we believe this.
3. Name the period in which we first commonly find evidence of life on land.
4. In which period was there sufficient plant life for the production of coal deposits?
5. Into what did air-breathing fish probably evolve during the Devonian Period?
6. What major events do geologists believe took place during the Cretaceous Period?
7. Give three reasons why animals become extinct.

SUMMARY

Through the study of fossils, geologists have been able to relate the many short sequences of sedimentary rocks found throughout the world. The Precambrian Era was one during which the dominant form of life was microscopic aquatic plants and animals. This was followed by the Paleozoic Era, during which trilobites lived; it was the era when fish reached a high degree of development.

The next era, the Mesozoic, was a time when life on the land developed rapidly. Reptiles were the most numerous of advanced types of animals. Conifers occupied the same position among plants. During the Cenozoic Era, modern plants and animals reached their present degree of development. The system of dating rocks by the fossils they contain yields relative, not absolute, ages.

REVIEW AND DISCUSSION QUESTIONS

1. Why is the Cambrian sequence of rocks believed to be older than the Silurian?
2. Describe how geologists use fossils in rocks to tell how old the rocks are?
3. How could you determine that rock layers in Europe and others in America were of the same age?
4. What determines when one era ends and another begins?
5. Why cannot the usual method for dividing an era be used for the Precambrian Era?
6. Explain any relationship between changes in the earth, as at the end of the Paleozoic Era, and the evolution of land animals.
7. How is the biological theory of evolution supported by geologic evidence?
8. Why did warm-blooded animals increase in number as many of the cold-blooded forms became extinct?

9. Explain how the increase in the number of one kind of life may affect the number of another kind of life.
10. Explain why climatic changes have a greater effect on land life than on marine life.
11. European geologists do not find it necessary to divide the Carboniferous Period into two major sections. American geologists divide it into the Pennsylvanian Period and the Mississippian Period. What does this suggest to you about the relationship between land and sea in Europe and in America at the time the sediments of these systems of rocks were being deposited?
12. When life emerged from the sea and began to live on the land, it changed in many respects. What basic changes do you consider were most necessary? Why?
13. We believe that during the Mesozoic Era the climate was uniform throughout the year. The Cenozoic was the next era. One of the features of the climate of this era was the development of changing weather conditions outside the tropics. How would you use this information to show why birds and mammals became the dominant large-life forms on the land? Why did reptiles begin to decline during the Cenozoic Era?

CHAPTER **8**

DATING THE EARTH

No one knows the answer to the question, How old is the earth? However, many guesses and estimates have been made—some bad and some good. Not very long ago, some people thought the earth was only about 6,000 years old. This is one of the bad guesses. We know there are very few rocks as young as 6,000 years old. On the other hand, most astronomers think the earth is at least 5 billion years old. These estimates depend on hypotheses that cannot yet be proved.

Because very few people live to be 100 years old, that seems a very long time to us. Very few animals live longer than man does, but many trees do. Some of the giant redwood trees in California may be 2,000 years old. The bristlecone pine tree, shown in the picture on the opposite page, is known to live almost twice that long.

To us, whose lives are shorter than a century, years are important. To geologists studying the ages of rocks, centuries mean little. Centuries are no more important to them than seconds are to us because geologists study rocks millions of years old. It has taken them a long time to discover how to tell the actual age of a rock. They tried many methods before they found one that was reasonably accurate.

8-1 BUFFON GUESSES 75,000 YEARS

The first scientific attempt to measure the age of the earth was made around 1770 by a French naturalist, Georges Buffon. He concluded that the earth was 75,000 years old. Buffon assumed that the earth began as a white-hot ball. Then he estimated how long it would take the earth to cool so that life could exist on it. He thought this would take about 35,000 years. To this he added 40,000 years to cover the time from the formation of Cambrian fossils until the present.

Bristlecone pine tree

Figure 8-1 Georges Buffon (French, 1707–1788). Buffon studied law and medicine and translated many scientific works from English to French. In his work, Buffon envisaged a concept of evolution. He also advanced a theory concerning the slow development of the earth. His attempts at dating the earth were the first to go beyond the 6,000-year limit, set by the Book of Genesis.

8-2 JOLY EXAMINES SALT IN THE OCEANS

In 1899 John Joly, an Irish scientist, made two assumptions about the earth's history: (1) The original oceans contained no salt. (2) The salt in the oceans once had been part of the rocks on the land. He then estimated how much salt was being added to the oceans by the rivers each year. He divided that figure into the amount of salt he had calculated to be in the oceans. Joly's calculations led him to the conclusion that the oceans were between 90 and 100 million years old. Joly knew this figure was not accurate. All he said was that the oceans were at least this old.

Joly realized that what he could *not* study was important. First of all, he knew that the flow of the major rivers was different in ancient times. Therefore, his guess at the amount of salt that enters the sea each year could not be accurate. He was also sure there were millions and millions of tons of salt buried in the earth. Joly did not know, and we do not know today, how much salt that had been in the oceans now lies buried in the earth.

8-3 SOLLAS USES SEDIMENTS

The next scientist to publish an estimate of the age of the earth was William Sollas, a British geologist. Sollas had spent many years studying the rates at which sediments form. From geologic rock systems, he gathered measurements on the thickness of sedimentary rocks. He used the thickest meas-

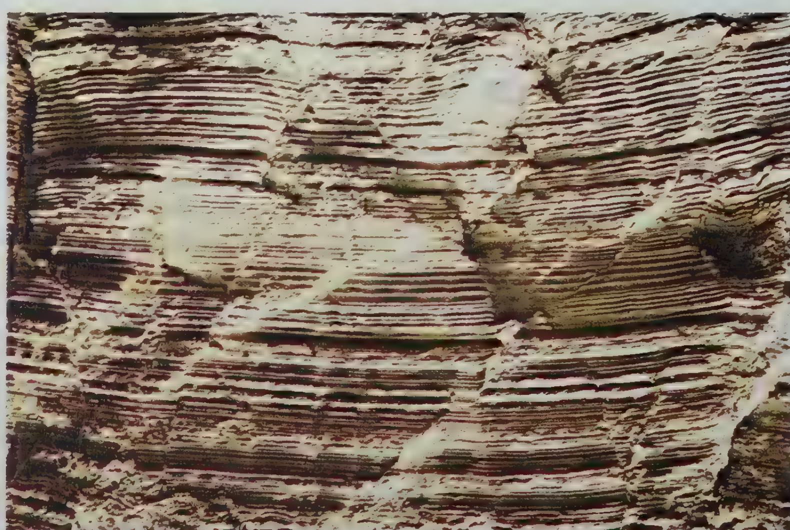


Figure 8-2 Columns of sediments that are deposited in layers within a year's time are called *varves*. Sometimes a contrasting pair of layers will represent seasonal deposits within a year.

urement from each system and added all the figures. Then he divided the sum by what he thought was the average thickness of one year's sediments. Sollas concluded that the earliest Cambrian rocks were at least between 26 million and 75 million years old (see note in margin). His conclusion was reasonable, but more important, it was based on scientific evidence.

What Sollas did not know, however, was the thickness of rock that had been worn away. Nor did he take into account the varying rates at which sediments are deposited. We do not fully know the answers to these questions even today. Sollas did not know exactly how much sediment was needed to make an inch of sedimentary rock. Today we know this factor is different for each kind of sedimentary rock.

Sollas and Joly knew that their conclusions would be useful. They gave us a minimum age for sedimentary rocks and the oceans. Sollas' wrong answers told us that the earliest Cambrian rocks were at least 26 million, and probably closer to 75 million, years old. Joly's wrong answer told us that the oceans in which the Cambrian rocks formed were at least 90 million years old.

Study Guide

1. Give two assumptions that Buffon used in estimating the age of the earth.
2. Give two assumptions that Joly used in estimating the age of the earth.
3. Give one assumption that Sollas used in estimating the age of the earth.

8-4 ATOMS ANSWER THE QUESTION

At about the time that Sollas was determining the minimum age of Cambrian rocks, Henri Becquerel made his great discovery (see Section 2-7). He accidently found that a sample of uranium emits invisible rays that can leave an image on a photographic plate. Becquerel's assistant, Maria Sklodowska, named the phenomenon **radioactivity.** This discovery has changed our lives in many ways. It changed things for geology, too, because it led to a method by which geologists could measure the absolute ages of rocks.

radioactivity. The property possessed by certain elements, such as uranium, of giving off alpha or beta rays and sometimes gamma rays by the decay of the nucleus of an atom.

We have all heard about radioactivity. Certain kinds of elements are naturally radioactive, and they behave differently from those that are not. One of these elements is uranium, U. A nonradioactive element such as silver or gold is always the same; it never changes under natural conditions. Radioactive elements do change. For example, a piece of uranium slowly changes to lead. Scientists have discovered how to measure the rate at which this change takes place. It is this information that has enabled them to use radioactive substances to date rocks.

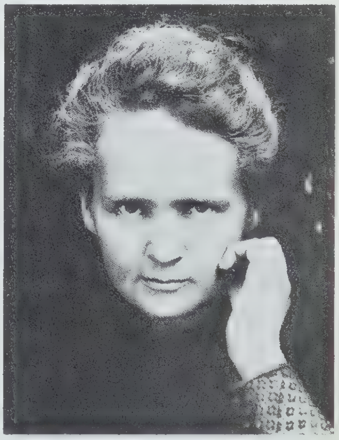


Figure 8-3 Maria Sklodowska Curie (Polish-French, 1867–1934). Her work on radioactivity and radium expanded on Roentgen's discovery of X rays. She is the only person to win two Nobel science prizes. In 1903 she shared the Nobel Prize in Physics, and she was awarded the Nobel Prize in Chemistry in 1911.

8-5 URANIUM ATOMS ARE CLOCKS

isotope; Greek: *iso*, equal + *topos*, position. Any of two or more species of atoms of the same chemical element that have the same atomic number but a different atomic weight or mass.

Uranium is a very heavy metal and has certain unique chemical properties by which chemists can recognize it. Many of the properties of uranium seem to be produced by the 92 electrons that swarm around the nucleus, or core, of the uranium atom. All natural uranium atoms have the same number of electrons in the same arrangement outside the nucleus. However, not all uranium atoms have the same kind of nucleus.

Atoms of the same element that contain nuclei having two or more different masses are called **isotopes**. Each nucleus of a different mass represents a different isotope. Thus, we have listed three isotopes of uranium. Uranium isotopes differ in the rate at which they change from uranium to another substance. This means that they differ in their radioactivity.

An atom of the common isotope of uranium, U-238, changes quite rapidly to an isotope of lead, Pb-206. However, the change does not occur in all atoms at the same time. For a large number of uranium atoms, as in a large piece of rock, the change from uranium to lead appears to take place slowly.

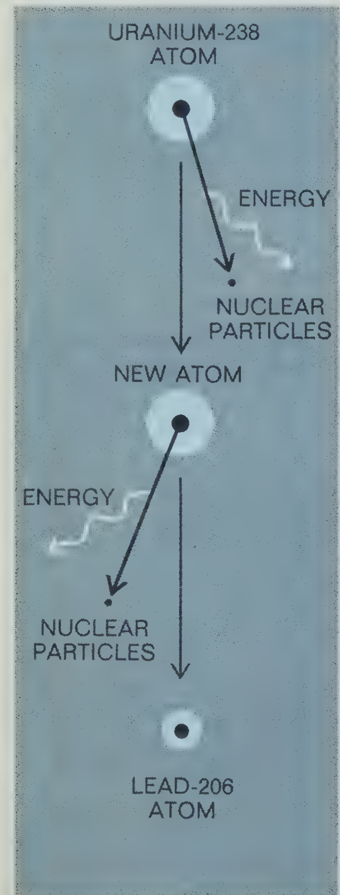


Figure 8-4 Alpha decay occurs in the uranium atom when particles leave the nucleus. This process continues to take place until the U-238 atom decays by radioactivity to an atom of lead.

The change, or **decay**, to lead occurs because the characteristics of the uranium atom cause it to lose both nuclear particles and outer electrons. It is the loss of these particles that is called **natural radioactive decay**. The atom decays until its new properties cause it to become stable. At this time, decay stops. So the nucleus of a U-238 atom undergoes natural decay until it becomes a stable Pb-206 nucleus (see Figure 8-4).

Nuclear fission, described in Section 2-7, is a form of artificial radioactive decay. In this case, all the material undergoes decay in fractions of seconds. The rapid release of the energy that held the nucleus together is what causes the destructive explosion. The first atomic bomb explosion was caused by the fission of a uranium isotope—U-235.

The rate of radioactive decay depends on chance. There is a fifty-fifty chance that a particular U-238 atom will decay about every 4.5 billion (4.5×10^9) years. Once the decay begins, it proceeds rapidly. In a relatively short time, the U-238 nucleus is reduced to a mass of 206, the mass of the lead isotope.

Because there is a fifty-fifty chance that decay will occur, scientists can measure the age of rocks. Imagine a mineral that contains uranium as part of its chemical makeup. At any time, some of the atoms are changing to lead, as shown in Figure 8-5. In the case of U-238, about one half of the origi-

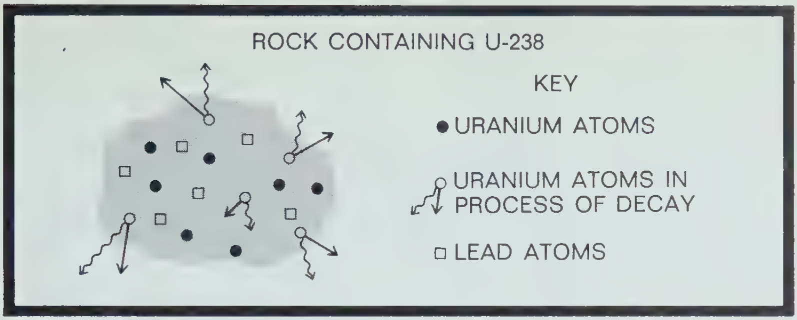


Figure 8-5 The lead content of a uranium-bearing rock increases with time because of the decay of U-238 atoms.

nal atoms will have decayed to Pb-206 in approximately 4.5×10^9 years. This length of time is called the **half-life** of U-238.

Scientists have used this knowledge to date mineral specimens that contain uranium. When the minerals were first formed, they contained no Pb-206—only U-238. As the crystal aged, some of the uranium changed to lead. By carefully measuring the amount of Pb-206 and U-238 in a specimen, it is possible to calculate how long ago the mineral contained no Pb-206—that is, when it was formed. For instance, if about 50 percent of the uranium has changed to lead, the mineral is about 4.5 billion years old.

Certain Precambrian granites in the Rocky Mountains have been dated this way and found to be about 1.2 billion years old. This means that less than one half of the original U-238 has decayed to lead. Among the oldest rocks dated with the aid of uranium are some igneous rocks from Rhodesia, in southern Africa. These are about 3.8 billion years old.

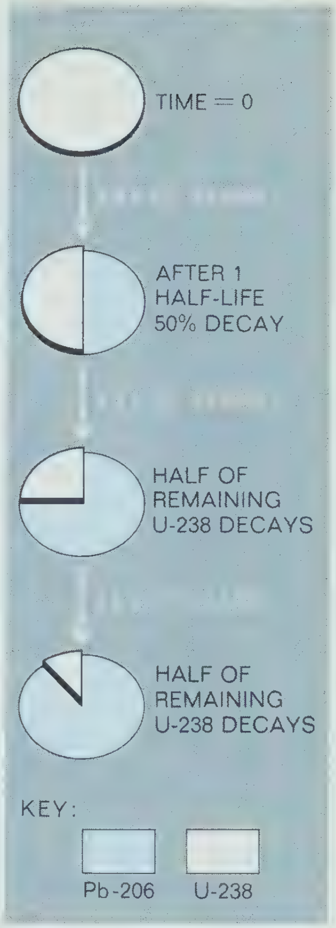


Figure 8-6 In this explanation of half-life, the time interval between each decay is 4.5 billion years. Will the mass of U-238 eventually decay to the extent that there will be no trace of uranium? Give a reason for your answer.

8-6 OTHER RADIOACTIVE ISOTOPES ARE USED

Minerals containing uranium in measurable quantities are found in few rocks. This means that the uranium-lead method cannot be used very often (see note in margin). There is, however, another method that is useful for dating rocks. Radioactive potassium is commonly found in many igneous and metamorphic rocks. The chemist's symbol for potassium is K. The important radioactive potassium isotope is K-40. K-40 slowly changes to argon-40 (Ar-40). The half-life of K-40 is 1.35×10^9 years. This is only one third as long as

If a mineral containing U-238 and the rock in which it is found were both formed at the same time, one can accurately date the rock by the age of the mineral.

the half-life of U-238. Therefore, the K-40 method can be used on younger rocks more accurately than the uranium-lead method can.

Since the discovery of how to measure the ages of rocks by using K-40, many crystalline rocks have been dated. Some are as young as a million years old.

None of the radioactive dating techniques are carried out easily. All require special laboratory equipment and very skillful chemists and physicists (see Figure 8-7).

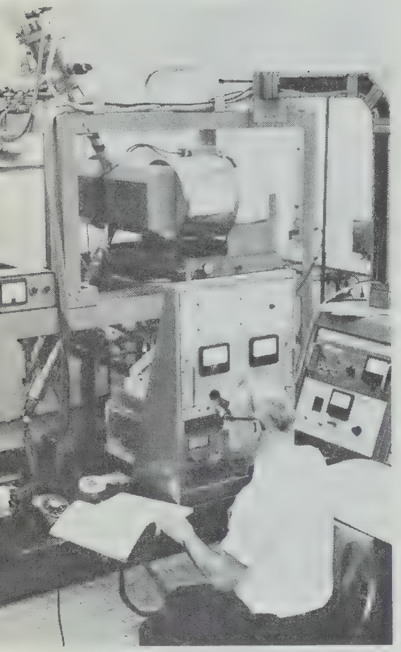


Figure 8-7 With a mass spectroscope it is possible to identify and to measure accurately the amount of an element in a mineral. A beam of ions is used instead of a beam of light to form a mass spectrum.

Several other radioactive elements are used for measuring the ages of rocks. It is often possible to use two radioactive-decay methods with a single sample. When this is done, and the two ages thus determined are reasonably close, we are more confident about the accuracy of the date.

In any case, the results of radioactive dating are much more accurate than any of the guesses previously made. The basic assumption of this method is that the rate of radioactive decay of an isotope is constant. The method does not give us an age for the earth, but it does give us a good estimate of the age of the earth's thin crust, which we can see and measure.

In addition to the chemical and physical problems involved in measuring the age of a rock, the geologic situation must be understood. For example, metamorphism affects many age determinations. The determination of the age of the gneiss found in the vicinity of Baltimore, Maryland, is a good example. The uranium-lead method gives an estimate of about 1.1 billion years. The potassium-argon method gives us an estimate of only 300 million years.

The reason for this great difference is that the minerals used for the uranium-lead method are affected little, or not at all, by metamorphism. Those used for the potassium-argon method are strongly affected by metamorphism.Geologists believe the Baltimore gneiss crystallized about 1.1 billion years ago. About 300 million years ago, the gneiss was affected by the metamorphism that occurred when the Appalachian Mountains developed. This seems to explain the difference.

Study Guide

1. Describe what makes an element radioactive.
2. What element does uranium ultimately decay to?
3. Explain the term *isotope*.
4. What is the half-life of an element?
5. When do geologists have confidence in the radioactive-decay method of determining the age of a rock?

8-7 AN ESTIMATE OF THE AGE OF THE EARTH

Recently, an English scientist, Arthur Holmes, carefully studied information from all over the world about the ages of rocks determined by radioactive dating. From this evidence he calculated that the thin crust of rocks on the surface of the earth cannot be older than 4.5 billion (4.5×10^9) years.

This is close to the estimate of most astronomers that the earth is about 5 billion years old. Some astronomers arrived at this estimate by observing the speed at which distant parts of the observable universe are traveling away from us. This method is based on the theory that in the beginning all the matter in the universe was concentrated at one place, and has since scattered. Most astronomers believe it has taken at least 5 billion years for this expansion to occur (see note in margin).

Some scientists doubt the accuracy of the method used by astronomers to arrive at their answers. There is a type of celestial body called a *quasar*. This body, which is something like a star, gives off both light and radio waves (see Section 34-15).

The astronomers used one method, and Holmes used an entirely different method. But both methods give about the same results. Thus, it seems that the earth may be about 5 billion years old.

8-8 RADIOCARBON

You have radioactive atoms in your body. All organisms contain some radioactive K-40. In addition, one of the substances of which we are made is carbon. Most carbon is made of the common isotope, C-12. A tiny fraction of the carbon in us is radioactive. It is called **radiocarbon**, or **carbon-14** (C-14). The half-life of carbon-14 is only about 5,800 years.

Living things acquire both C-12 and C-14 through the food they make or eat. They gain amounts of radiocarbon in proportion to their weight. The ratio of C-14 to C-12 remains the same in an organism's body as it is in the earth's atmosphere.

When plants and animals die, they no longer gain new radiocarbon, and the radiocarbon that is in them continues to decay. By comparing the amounts of C-12 and C-14 in the actual remains of living things, we can estimate their ages. Although it is possible to estimate ages as great as 70,000 years by the radiocarbon method, most scientists agree that the method is not very useful for ages greater than from 30,000 to 35,000 years. Therefore, radiocarbon dating is useful only for geologically recent events.

One of the events geologists have studied closely is the movement of the great ice sheets that covered much of the Northern Hemisphere in the recent past. In North America the land from the Ohio and Missouri rivers northward was at one time buried under thousands of feet of ice. The south-

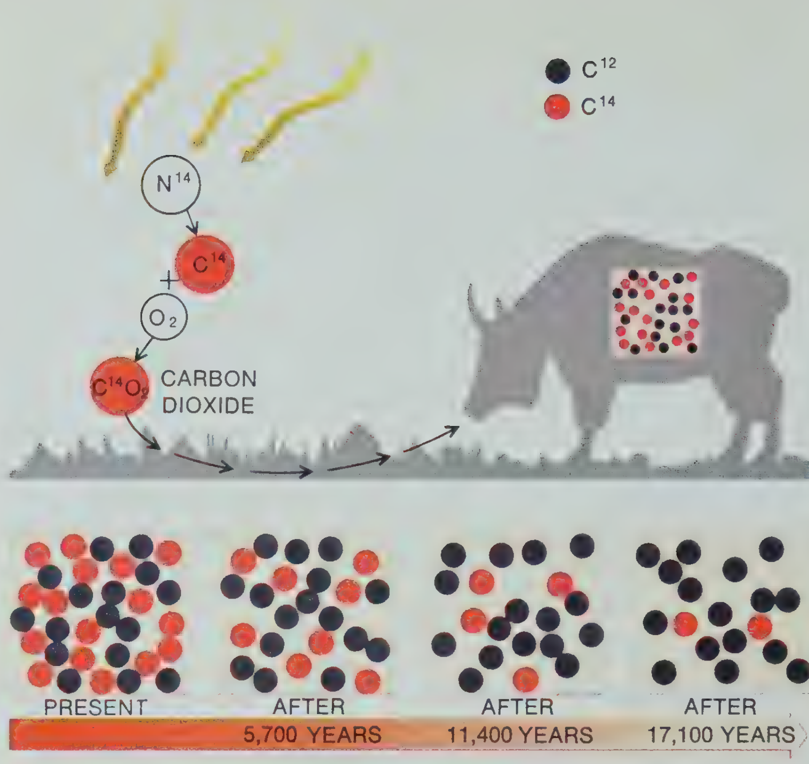


Figure 8-8 Radiocarbon dating can be used to determine the approximate age of an organism. Nitrogen-14 is changed to carbon-14 high in the atmosphere through bombardment by cosmic rays. The carbon-14 finds its way into plants and eventually animals. The amount of carbon-14 in the animal shown in this diagram corresponds to the amount of carbon-14 in the first box below the cycle.

ward movement of this mass of ice buried parts of trees under great piles of rock debris deposited by the ice. When the remains of these trees are studied for the radiocarbon they contain, we get an estimate of when they became buried. From such evidence it seems that the northern part of our Midwest was under the ice as recently as 11,000 years ago.

8-9 ABSOLUTE DATES AND THE GEOLOGIC COLUMN

It would be very helpful if we could always find at just the right place in a sequence of rocks the minerals that can be used for radioactive dating. Unfortunately, this does not happen. The dates we have gathered are from scattered places in the geologic column—very rarely at the beginning or the end of a period.

The dating of the beginning of the Cenozoic Era is an example of how geologists estimate the age of a particular era or period. In Gilpin County, Colorado, there is a deep mass of igneous rock that contains radioactive minerals. This is below a layer of Cretaceous sedimentary rock that is, in

turn, below a layer of Tertiary sedimentary rock. In this particular formation, the igneous rock has cut through the Cretaceous rock but not through the Tertiary rock. This situation is shown in Figure 8-9. The age of the upper layer of igneous rock is therefore between that of the Tertiary and the Cretaceous layers.

Using the principles of superposition and uniformitarianism, geologists have established three dates for this formation. The first is a relative date: The Tertiary Period occurred after the Cretaceous. The second date is also relative: The crystalline rock was formed after the Cretaceous sediments but before the Tertiary. The third date is an absolute age: Using radioactive dating techniques, the minerals in the crystalline rock were found to be about 60 million years old.

Geologists concluded that the Mesozoic Era ended and the Cenozoic Era began at least 60 million years ago. But since we know that this particular Tertiary sedimentary rock is not the oldest Tertiary rock that has been found, we have added 10 million years to the age of the Tertiary Period. Thus, the Cenozoic Era is thought to have begun approximately 70 million years ago. A geologic time scale with estimates of the ages and the duration of the eras and periods is given in Table 8-2.

Chapters 6-8 have shown you how important sedimentary rocks are to geologists. Buried in these rocks is the story of the last few billion years of the earth's history. To better understand these sedimentary rocks, we will have to investigate the sediments from which they were formed. We need to know the sources of the sediments, how the sediments accumulated, and how they ultimately became rock.

Figure 8-9 In Gilpin County, Colorado, sometime at the end of the Cretaceous Period, an intrusion of molten radioactive rock forced its way over Cretaceous rock.

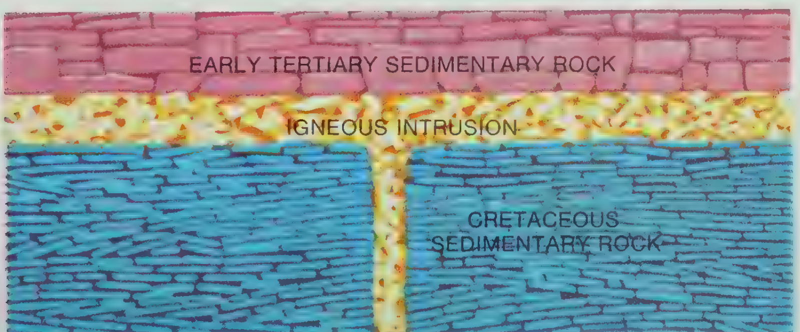


Table 8-2 Geologic column and time scale

Era	Period	Duration (millions of years)	Beginning (millions of years ago)
Cenozoic	Quaternary	2	2
	Tertiary	68	70 ± 2
Mesozoic	Cretaceous	65	135 ± 5
	Jurassic	45	180 ± 5
	Triassic	45	225 ± 10
Paleozoic	Permian	45	270 ± 10
	Carboniferous	80	350 ± 10
	Pennsylvanian	50	320 ± 10
	Mississippian	30	350 ± 10
	Devonian	50	400 ± 10
	Silurian	40	440 ± 10
	Ordovician	60	500 ± 10
	Cambrian	100	600 ± 50
Precambrian	Proterozoic	1,900?	2,500?
	Archeozoic	1,000?	3,000+?
Azoic		???	5,000?

Study Guide

1. What is the present estimate of the age of the earth's crust?
2. Upon what is this estimate based?
3. What is the half-life of radiocarbon?
4. When and how do living organisms acquire radioactive carbon?
5. Explain how ice sheets have been dated.
6. Give the relative and the absolute dates that geologists used in dating certain rocks of Gilpin County, Colorado.

SUMMARY

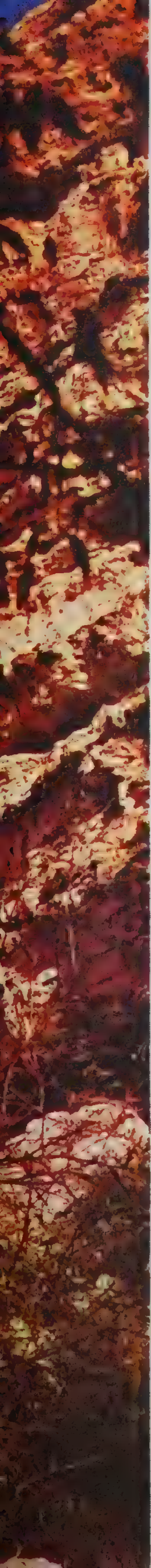
There have been many attempts to find a reliable method for estimating the age of the earth. Each of the methods has established a minimum age. The most successful method, and the one that has

had the widest use, involves radioactive isotopes. By using various isotopes, events as recent as 1,000 years ago and as distant as 3.8 billion years ago have been dated.

Only reasonably accurate dates are known for the beginnings of the geologic periods. These are based on ages of events that occurred within the periods and on estimates of when the periods began.

REVIEW AND DISCUSSION QUESTIONS

1. Explain why it is probably impossible to establish a precise date for the beginning of any geologic period.
2. What does the word *assumption* mean?
3. Give three examples of assumptions from this chapter.
4. What problem arises in the attempt to use the salinity of the oceans as a means of determining their age?
5. Why can the thickness of sediments not be used for accurately estimating the age of the earth?
6. Why was Joly's estimate of the earth's age a minimum age and not a maximum age?
7. How do radioactive elements differ from all others?
8. Explain why carbon-14 could or could not be used for dating a concrete building.
9. What is the major assumption that must be used in dating an object by the carbon-14 method?
10. Why is K-40 more useful in radioactive dating than U-238?
11. How can metamorphism affect radioactive dating?
12. One of the radioactive isotopes formed in the atmosphere is hydrogen-3. It has a half-life of 12 years. If one gram of hydrogen-3 were put in a safe place in 1970, how much would remain in 1982? When would five half-lives have passed for this sample, and how much hydrogen-3 would remain?
13. Explain why radioactive dating will not cause geologists to change the order of the periods.
14. The explosion of nuclear devices in the air produces particles that react with nitrogen to form carbon-14. Why will such explosions interfere with carbon-14 dating in the future?



CHAPTER 9

THE SOURCES OF SEDIMENTS

Early man must have seen great masses of soil and trees and rocks slip down a steep hillside. He probably saw rocks fall from a cliff and crash to the ground below. If he thought the way most primitive men do today, he probably explained this by saying that the cliff or some demon deliberately threw the rocks to the ground. As man became more thoughtful and lost his belief in evil spirits, he realized that the landslides and falling rocks had a natural explanation. It took man centuries to arrive at the explanations we now use.

9-1 NATURAL FORCES AT WORK

Two forces are important in explaining why some pieces of rock tumble from cliffs and why the soil on some hillsides slips downward. One of these forces is gravity, the attracting force that exists between two masses.

An object on a sloping surface will sometimes stay in place and sometimes slide down the slope. What holds it in place on the slope is friction, the second important force. **Friction** is the resistance to sliding.

There are two kinds of friction—**static friction** and **kinetic friction**. The first must be overcome to start an object sliding. The second kind must be overcome to keep the object sliding. The two kinds may require the same amount of force, as in the case of moving a very cold block of ice on an equally cold ice surface. However, they may require two quite different forces, as when you drag a heavy block of wood along the ground. In this case, it takes more force to overcome static friction than it does to overcome sliding friction.

In the case of loose debris on a slope, the force that overcomes static friction is the force of gravity. Once inertia has been overcome, the chances are very good that gravity will cause the moving mass to slide downhill until it comes to rest

Weathered limestone cliff dwellings, Montezuma Castle National Monument, Arizona

Figure 9-1 Talus formations occur where rock debris collects at the foot of a steep descending slope.

at the bottom of the slope. Jumbled debris formed in this way is called **talus**; and the slope covered with it, a **talus slope** (see Figure 9-1).

Soil on a hillside is usually composed of small particles that are irregular in shape. The individual particles are in contact with one another, and there is friction between their uneven surfaces. Friction between soil and bedrock holds the soil in place as long as the slope is not too steep. At the same time, gravity is attracting these soil particles and exerting a force on them. On a stable hillside, gravity is usually not sufficient to cause the particles to slip downhill. However, anything that reduces the friction between particles or between the soil mass and bedrock increases the chance of sliding.

When we want a machine to run smoothly, we use oil to lubricate the surfaces that rub against one another. This reduces the friction between the two moving surfaces. Many fluids are good lubricants. Water is a very good one, if the temperature of the surfaces to be lubricated is not high enough to cause the water to evaporate rapidly. How might soil be lubricated by means of natural phenomena? Wet soil on a hill tends to slide downward.

The movement of soil and rock may be rapid or slow. Rapid downslope movement results in landslides, rockslides, and mudflows (see Figure 9-2). In contrast, the movement of

Figure 9-2 Landslides and soil creep are more frequent in the spring than at other times. The water that has been frozen in the soil during the winter thaws and supplies abundant lubrication. Not only does water lubricate soil particles, but it also adds mass to the soil. With increased mass, there is a greater chance that the soil will slide.

material may occur so slowly that often years pass before noticeable changes take place. Such movement is called **soil creep**.

9-2 FROM ROCK TO SOIL

Neither Hutton nor the earlier observers knew how soil, from which sediments are made, was formed. But they knew, for instance, that ice forming in the cracks in a rock can force a piece of the rock to break loose. They knew that fragments of rock that fall a considerable distance often shatter when they strike other rocks. In Hutton's time, people understood some of the physical reasons for soil formation but none of the chemical reasons. Even today we do not know all the answers to the question, How is soil formed?

Soil is produced from the breakdown of rocks—sometimes directly from the bedrock that occurs at the surface and sometimes from small fragments of rock that have broken loose. Every kind of rock—igneous, metamorphic, and sedimentary—produces soil.

The term **soil** is restricted to the finely divided particles that lie on the earth's surface. Soil usually contains organic materials and is capable of supporting plant life. Figure 9-3 shows a soil profile, the layers of soil on the earth.

Figure 9-3 Soil profiles such as the one shown consist of a ground cover of plant life, topsoil, subsoil, broken rock, and bedrock. Why would a soil profile for deserts be different?

Geologists call all loose surface material **debris**. Debris is produced from solid rock by two kinds of action—one physical and the other chemical. The physical breakdown of rock changes the size of the pieces but not their chemical makeup. Chemical breakdown changes the composition of rock. It is very rare that only one of these actions is involved. Usually, the debris we see is the result of both physical and chemical breakdown.

The action of changing solid rock to debris is called **weathering**. It has been given this name because the "elements" of the weather—heat, cold, rain, and snow—cause rocks to break into smaller, loose pieces. The air itself also plays a large part in weathering.

Study Guide

1. Give a definition for each of the two kinds of friction.
2. What force may overcome friction and cause stones and soil to slip down a slope?
3. What factors determine how much force must be applied to overcome friction?

Figure 9-4 The mineral grains that compose a rock expand at different rates when heated. Those grains most affected press strongly against neighboring grains when the rock is hot. When the rock is cold, the grains draw apart, splitting off, or spalling, thin layers of rock.

4. What is the effect of water on friction between soil particles?
5. How is soil formed?
6. Name the agents that cause weathering.

9-3 THE EFFECTS OF HEAT ENERGY

Probably the most important kind of energy that brings about the physical breakdown of solid rock is heat. Physicists have observed that when heat energy affects a substance, two things occur: The substance gets warmer, and it expands. The change in temperature is much more easily observed than the expansion.

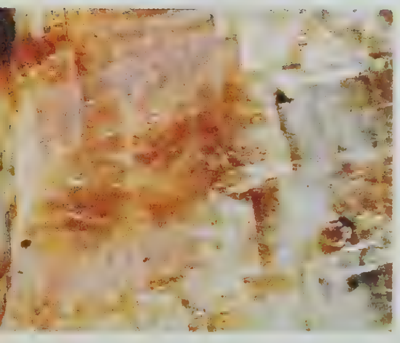


Figure 9-5 These microcracks, formed in pink calcite, were found in Franklin, New Jersey.

The effects of heating and cooling on rocks is most noticeable in desert areas, where days are hot and nights are cold. The effects are not restricted to deserts but occur wherever there are large changes in temperature. Rocks are poor conductors of heat. This means that while the surface of a rock may feel uncomfortably hot to your hand, the interior of the rock is cool.

The uneven heating and expansion of rock may cause thin layers to split off, as shown in Figure 9-4. Over a long period of time, expansion and contraction cause tiny cracks in the rock, as shown in Figure 9-5. The mineral grains loosen, and when it rains or when snow melts on the rock, water fills the tiny cracks.

Figure 9-6 The violent explosive force of water confined in a small space and frozen is demonstrated in these two photographs. This principle is similar to what happens when water freezes in cracks in rocks.

9-4 THE EFFECT OF FREEZING WATER

Water is a curious substance. We are so accustomed to water that we seldom realize how important and unusual it is. For instance, it is one of the very few substances that expands when it freezes (see Figure 9-6). If this did not happen, ice would be denser than water and would not float. In summer the oceans in the colder latitudes would be a thin layer of water on top of solid ice. The earth would be quite a different kind of place than it is now. In fact, it seems quite probable that much of the earth would be without life.

In winter when nights are cold enough, water freezes in the tiny cracks in a rock. When this happens, the water expands and presses against the rock at the sides of the crack. If the water expands enough, the rock will break (see Figure 9-7). When this happens, a little piece of the solid rock becomes part of the earth's debris.

Figure 9-7 Freezing on the face of a granite cliff will result in irregular breakage. This is caused by expanding ice crystals in the cracks.

Study Guide

1. In what ways does heat energy affect a substance?
2. Why does ice float?
3. What may be the effect of rapid heat changes on a rock?
4. Explain how freezing water can cause a rock to break.

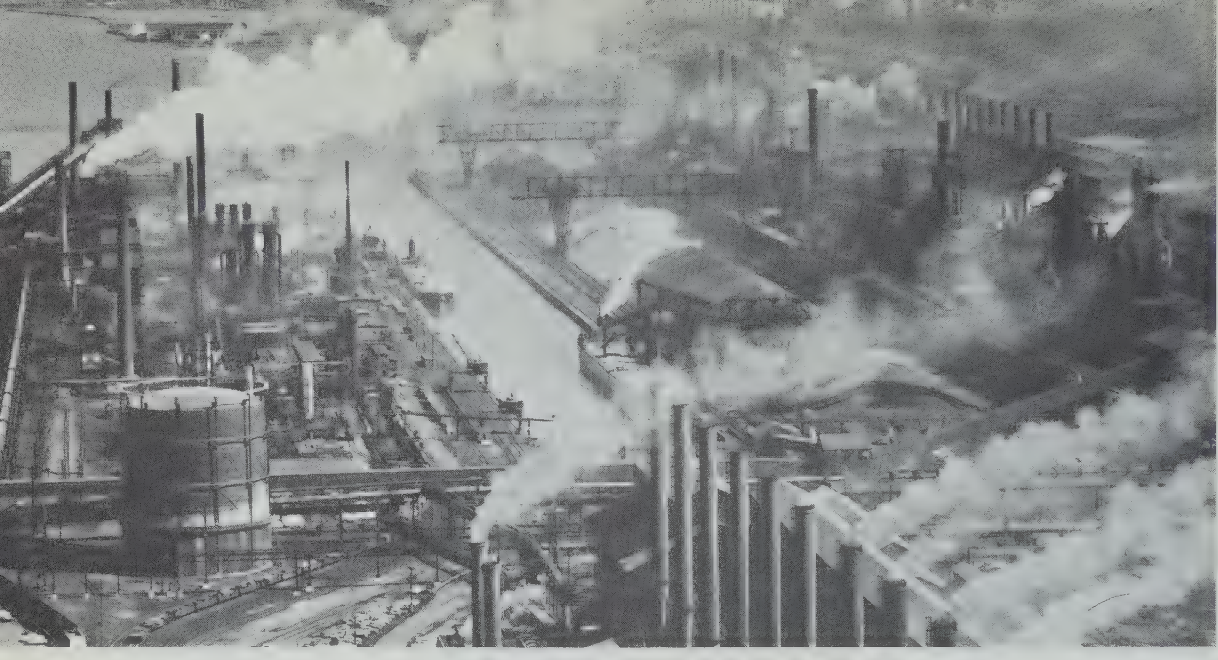


Figure 9-8 The gases given off by the smokestacks of this steel mill are hydrogen sulfide (H_2S), sulfur dioxide (SO_2), sulfur trioxide (SO_3), and hydrogen chloride (HCL). These gases combine with water to form acids that corrode minerals.

9-5 CHEMICAL WEATHERING

We have seen how physical agents, especially heat energy, can slowly break down rocks to debris, which then becomes soil. Another action that forms debris is chemical action, or **chemical weathering.** The atmosphere that surrounds the solid earth is a mixture of gases. One of them is oxygen (O_2), a very important chemical element that constitutes about one fifth of the atmosphere. Two other gases found in the lower parts of the atmosphere are carbon dioxide (CO_2) and water vapor (H_2O). These three gases react with rocks to bring about chemical changes.

In some regions, there are other gases in the atmosphere actively attacking the minerals in rocks. These gases exist naturally in volcanic areas, and are man-made in industrial areas (see Figure 9-8).

9-6 THE EFFECTS OF WATER

Water vapor plays a larger part in weathering rocks than does any other atmospheric gas. Without water vapor, none of the other active gases have much effect on the minerals in rocks. However, many gases, when they are in a water solution,

react with certain minerals. In such a reaction the mineral is changed, and often converted from a firm, solid mineral grain to a loose, powdery material.

Minerals and rocks respond in various ways to water and atmospheric gases. In general, if a mineral is formed in the presence of water, water itself will not chemically change the mineral. Quartz is an excellent example of such a substance.

What happens to those minerals that were formed at very high temperatures and under great pressure deep underground? When such minerals are exposed on the surface of the earth, they are in an environment very different from the one in which they were formed. This makes them unstable at the surface of the earth. If they are unstable when exposed to the atmosphere, chemical weathering takes place and produces new minerals from the old. The new minerals are likely to be stable in the environment of the earth's surface.

Water alone can attack minerals in several ways. Those minerals that are soluble in water are dissolved and washed away. Halite, the mineral we use as table salt, is an example. Gypsum is another.

Water also **hydrates** certain minerals. This means that a mineral chemically combines with water. In doing so, the mineral often expands, shatters, and is reduced to a powdery mass. The mineral anhydrite ($CaSO_4$) reacts with water to form gypsum (see Figure 9-9). In doing so, it swells and may fracture overlying rocks.

Figure 9-9 When anhydrite ($CaSO_4$) reacts with water to produce gypsum ($CaSO_4 \cdot 2H_2O$), it increases about 25 percent in volume.

As we have seen, several gases of the air—oxygen, carbon dioxide, the sulfur gases, and hydrogen chloride—dissolve in water. Their water solutions attack certain minerals. For example, pyrite (FeS_2) is attacked by water containing oxygen. This action converts the sulfur in the pyrite to sulfuric acid, which in turn attacks other minerals that are nearby.

Carbon dioxide in combination with water forms carbonic acid (H_2CO_3). This acid can change relatively insoluble calcium carbonate ($CaCO_3$), also known as calcite or limestone, into soluble calcium bicarbonate ($Ca(HCO_3)_2$).

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$$

The other gases mentioned also form acids when dissolved in water and can then attack minerals.

Since most rocks are composed of a mixture of minerals, the various actions of water and atmospheric gases remove or change some of the minerals, thus loosening those that are not affected. These loosened mineral grains, mostly quartz sand, become part of the debris formed by weathering.

Study Guide

1. Define chemical weathering.
2. List the gases in the atmosphere that attack rocks.
3. Why can't certain gases in the atmosphere react with minerals?
4. The gases of the atmosphere do not react readily with quartz. What does this tell you about where and how quartz forms?
5. What types of rocks react most readily with chemical weathering agents?
6. Name two ways in which water attacks minerals.

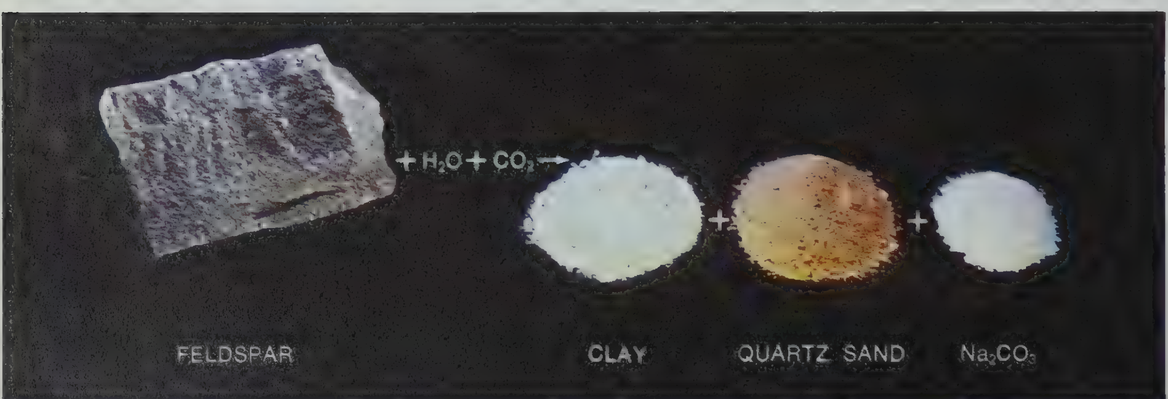
9-7 THE WEATHERING OF FELDSPARS

In regions where large areas of the surface rocks are limestones, the action of water containing carbon dioxide produces a certain type of landscape (see Section 16-5). In limestone areas very extensive systems of caves are found. Often in such regions there are no streams running on the surface, but they do occur underground.

Feldspars are the most abundant family of minerals found in igneous and metamorphic rocks. In spite of this, they are uncommon in sedimentary rocks. This means that feldspars are uncommon in the sediments formed from the chemical weathering of igneous and metamorphic rocks. Feldspar is a hard mineral, almost as hard as quartz; yet it is easily weathered by water that contains dissolved carbon dioxide.

Feldspars are complex substances that contain silica, aluminum, and active metals such as sodium, potassium, or calcium. Carbonic acid attacks and combines with the active-metal part of the feldspar, as shown in Figure 9-10. This combination forms a new compound, a carbonate of the active metal. For example, if the metal is sodium, then sodium carbonate (Na_2CO_3), or washing soda, is formed. If it is potassium, then potassium carbonate (K_2CO_3) is formed. These carbonates are soluble in water and thus are washed away.

Figure 9-10 Weathering of feldspar by water and carbon dioxide produces insoluble clay, insoluble quartz, and water-soluble alkali carbonates.



Two minerals remain. One of these is quartz (SiO_2), shown in Figure 9-10. The other is **clay,** a group of minerals formed from water and the aluminum and silica of feldspars. Thus, a very weak solution of carbonic acid, which you are not afraid to drink in soda pop, destroys the hard mineral feldspar and separates it into a soluble carbonate, quartz, and soft clay. The soluble carbonate washes away, and the insoluble quartz and clay remain.

Figure 9-11 Tombstones are weathered by physical processes. The effects of water, heating, and cooling will eventually cause them to crack.

9-8 THE WEATHERING OF SEDIMENTARY ROCKS

Since a great many sedimentary rocks are formed from quartz and clay, chemical weathering has little effect on them. Such rocks are made from minerals that are stable in the environment of the earth's surface. Almost all the weathering of such rocks results from physical processes. Figure 9-11 shows physical weathering of brownstone, a sandstone once used for buildings and tombstones.

There is one type of sedimentary rock, however, that is easily weathered by chemical agents. This is limestone, a rock rich in calcium carbonate. Remember, this can be dissolved by carbonic acid. Some limestones are almost pure calcium carbonate, while others contain varying amounts of clay and sand. Thus, rainwater, which contains carbon dioxide, dissolves the calcium carbonate from limestone and leaves behind the loose, insoluble grains of sand and clay (see note in margin of page 116).

Figure 9-12 The pressure built up in the cells of the roots of this young tree has caused the rock to split. How does this action similarly affect sidewalks and streets?

9-9 THE ACTION OF PLANTS AND ANIMALS ON ROCKS

Usually, we think of a growing seedling as a very delicate organism. And it is, in certain respects. It requires just the right amount of water and sunlight for growth. It is difficult to imagine such a weak thing as a young plant breaking rocks (see Figure 9-12). The force that enables plants to break rocks is the result of water pressure in the cells of the roots.

Another kind of plant, a lichen, shown in Figure 9-13, attacks rock surfaces in a different way. To do this, it secretes acids that dissolve some parts of minerals such as feldspar and mica, leaving the rest behind as clay. This is one way that rock is changed to soil. Lichens also allow some water to come in contact with the rocks. In winter, as this water freezes and thaws, it helps to break loose tiny bits of rock.

As we have seen, the activities of man have a direct effect on rocks. We, of course, reduce rock to debris when we mine, quarry, and build highways. The sulfur gases we produce in

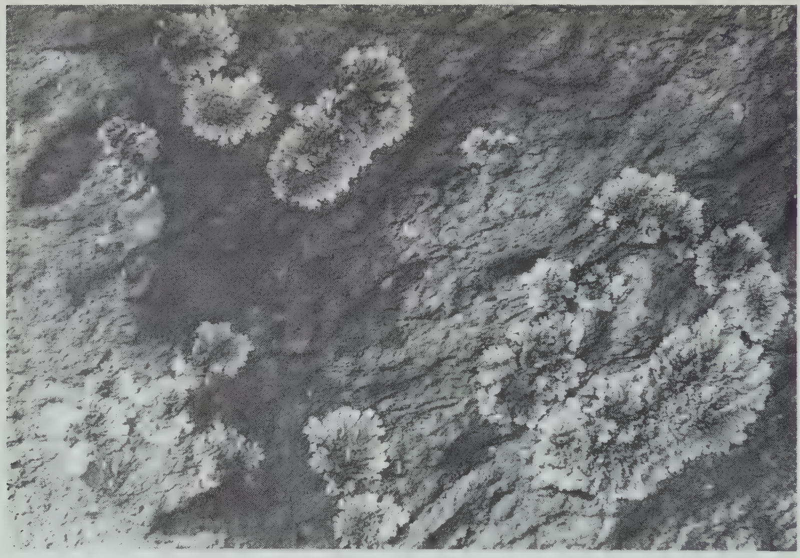


Figure 9-13 Lichens are a combination of an alga and a fungus growing together. Many of them grow only on rock surfaces. They get the minerals they need from the rock.

our industrial plants pollute the air and form acids that attack not only rocks but also our lungs and eyes. The carbon dioxide we add to the air by burning such fuels as wood, coal, and oil increases the weathering of certain rocks in our urban and industrial areas. This happens not only to the rocks in nature but also to the rocks we use in building.

Study Guide

1. What is feldspar made of?
2. Name the chemical compound that weathers feldspar.
3. What soluble chemicals are formed when feldspar weathers?
4. What materials are left behind when feldspar weathers?
5. What is clay?
6. Name two minerals that are often found in sedimentary rocks.
7. What kind of rock is limestone? What are the names of the elements it is composed of?
8. Describe two ways in which plants break down rocks.

SUMMARY

Weathering is the term used to describe all the ways by which physical and chemical actions break down rocks. The most common weathering agent is water. This substance, acting alone,

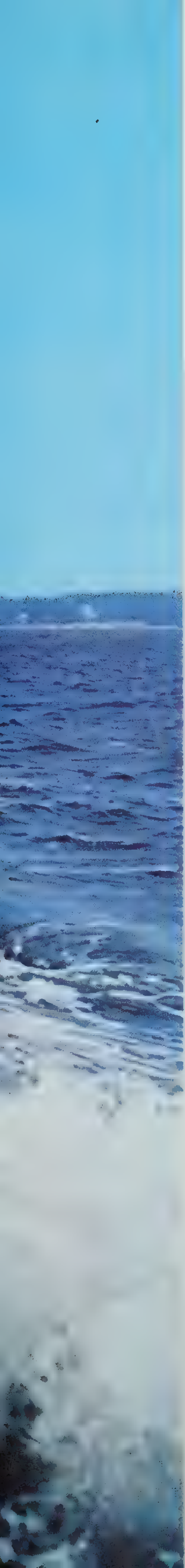
weathers rocks because of its physical and chemical properties. Because water expands when it freezes, it widens some cracks and breaks loose fragments of rock. It dissolves some minerals and alters others, reducing them to loose particles. Certain gases of the atmosphere combine with water to form acids. These acids dissolve certain minerals. Plant roots can penetrate small cracks and enlarge them, often breaking loose particles of the rock in the process. The action of weathering produces debris, which running streams can then transport as sediments.

REVIEW AND DISCUSSION QUESTIONS

1. Explain why landslides are more common in spring than in winter.
2. In what way is water an important factor in the development of sedimentary rocks?
3. In New England, there are many old fences that were originally built across the slope of a hill. The fence posts were originally vertical; they now lean downhill. Explain how this may have happened.
4. A sign frequently seen along newly built highways cut into the side of a mountain is "Caution! Falling Rocks." Why are such signs necessary even though the builder has removed all loose rock from the vicinity of the road cut?
5. Many kinds of animals, such as earthworms, ground squirrels, and foxes, excavate tunnels in the soil. How does this action aid the weathering of the soil?
6. The moon has no atmosphere and no surface water. Will the astronauts who land there find any evidence of weathering? Explain your answer.
7. The peninsula of Yucatán in Mexico is a low-lying land composed of limestones. It has a very heavy rainy season. There are no surface streams in the limestone area of Yucatán. Explain this curious situation.
8. Many snow slopes that are quite safe to cross on skis all winter become dangerous to cross in early spring. Why?
9. There is a difference of about 200C° (360F°) between "night" and "day" temperatures on the moon. How does this help to explain the loose debris that we have photographed on the surface of the moon?
10. Why does a pile of rock debris accumulate at the foot of a granite cliff in desert country?

CHAPTER **10**

WATER IN THE AIR



Have you ever watched water running from a garden hose onto the ground? What happens? The water washes away some of the soil where it strikes the ground. This wearing away of the soil is called **erosion**. Streams erode the land over which they flow. Water also moves the particles it erodes from the soil. This is called **transport**. A stream of water will slow as it flows from a steep slope into a more gentle slope or as it enters a lake or ocean. First the larger particles, then the smaller particles settle out of the water. This settling is called **deposition**. Thus, a natural stream does three things that can be observed: It erodes the soil, transports the load it carries, and deposits it.

10-1 STORED AND MOVING ENERGY

The three actions performed by streams involve work, and as we know, energy is needed to do work. The kind of energy that is at work in a stream is **mechanical energy**. There are two states of mechanical energy—potential and kinetic. **Potential energy** is stored energy. It is energy that is available for use but is not causing movement. As soon as an object begins to move, potential energy is changed to **kinetic energy**—the energy of motion.

The work that is done by a stream of water from a hose is the result of the kinetic energy of the flowing water. This energy, in turn, is derived from the potential energy the water has while resting in a reservoir, high above the point where it splashes to the ground from the hose. Geologists are interested in the action of streams and rivers. The water of these streams does the same kind of work that the water running from a hose does. It erodes its bed, transports debris, and deposits the debris.

How does a stream get energy to do its work? We cannot see work being done by a quiet puddle of water. The only

Drops of water evaporating and being flung from ocean waves

Figure 10-1 This cloud is called a *lenticular* cloud. It resembles a double convex lens because it thins out at the rim from a thick center.

time we can see water doing work is when the water is moving. It does this when the place from which it flows is higher than the place to which it goes.

How does water get to higher places? Clouds, such as the one in Figure 10-1, form and produce rain or snow, which falls to the ground. The water then flows into streams and rivers, and much of it ultimately flows into the oceans. The water that originally formed the clouds had evaporated from the oceans. This change from liquid water to water vapor requires energy in the form of heat. Water vapor forms clouds; rain or snow occurs; the water finds its way back to the oceans; and the whole process is repeated. Some of the water evaporates and changes back to water several times before it gets to the oceans again. This cycle is called the **hydrologic cycle** and is pictured in Figure 10-2. Now let us study this cycle more carefully.

10-2 HOW WATER LEAVES THE OCEANS

The oceans cover almost three quarters of the surface of the earth. Unlike the water in reservoirs, ocean water cannot flow out of its container. To do so, the water would have to flow uphill.

Water evaporates from the oceans in the form of water vapor. (See the photograph at the beginning of this chapter.) This action requires energy, just as the boiling of water (converting it to vapor) requires energy. Of course, ocean water never reaches the temperature of boiling. As heat from

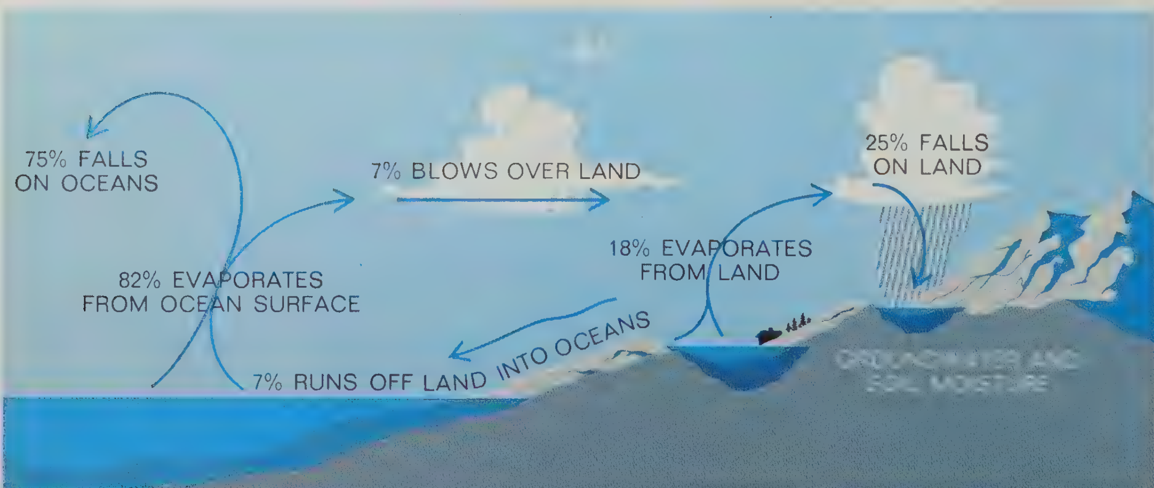


Figure 10-2 The hydrologic cycle includes the condensation, evaporation, and precipitation of water. How does this cycle uphold the laws of conservation of mass and energy?

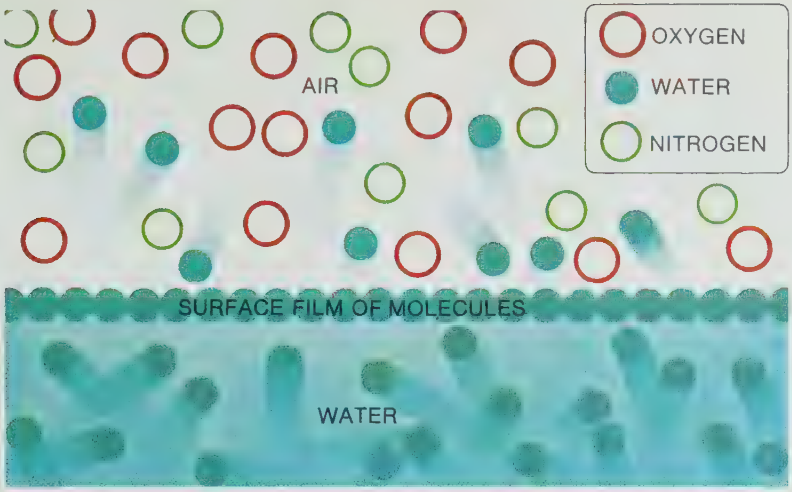


Figure 10-3 Water molecules near the surface of the water are moving fast enough to leave the surface film as water vapor.

the sun warms the surface of the ocean, the molecules of water move faster. When a molecule has gained enough energy, it moves so fast that it may leave the liquid water and become water vapor in the air. Figure 10-3 illustrates how water may evaporate. Some of the energy transferred to the water molecule has been changed to the kinetic energy of the water-vapor molecule.

Study Guide

1. Does the water in a reservoir contain potential energy, or kinetic energy? Explain your answer.
2. Explain how water gets from the ocean into a reservoir.
3. How does heat cause evaporation?

10-3 HEAT AND TEMPERATURE

Both heat and temperature can be thought of in terms of molecular motion. **Heat** is the total motion of the atomic particles of an object. Temperature is the measure of the average motion of the atomic particles of an object.

You know that there is a relationship between temperature and heat. You also know that temperature is the measure of the "hotness" of an object. The addition of heat to the mercury in a thermometer increases the motion of the mercury molecules. This increased motion causes the mercury column to expand and rise. The subtraction of heat from the column of mercury contracts the mercury, which falls. In other words, the rise and fall of the mercury column measures the effect of heat on the mercury.

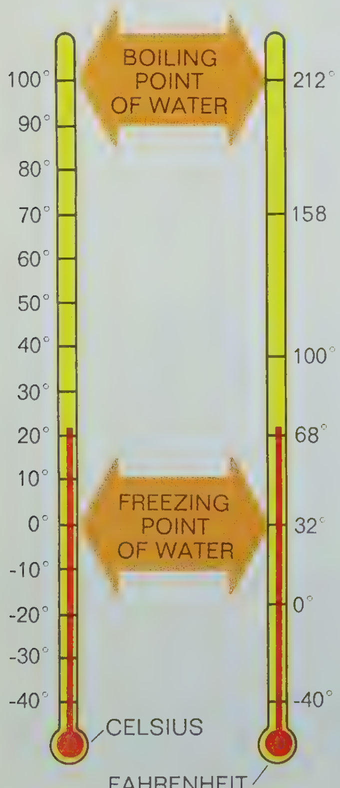
A scale commonly used in the home is the Fahrenheit scale. This scale, abbreviated F, is divided into 180 degrees between the boiling point of water (212°F) and the freezing point of water (32°F). Weather reports are almost always given in the Fahrenheit scale.

Scientists measure temperature with a scale that has 100 **degrees**, or steps, between the boiling and the freezing points of water at sea level. This temperature scale is called the **Celsius scale** and is abbreviated C (see note in margin).

Heat, on the other hand, is measured in units called **calories**, just as length is measured in units called inches or meters. One calorie is defined as the amount of heat that will raise the temperature of 1 gram of water 1 Celsius degree.

Suppose a liter of water at 20°C contains 20,000 calories more than a liter of water at 0°C. If you pour half the 20°C water into another container, each half liter will be at the same temperature of 20°C. But each half liter will contain only 10,000 calories more than a half liter of 0°C water. How does this example illustrate the difference between heat and temperature?

Figure 10-4 Scientists use the Celsius scale for recording temperatures. This diagram shows the boiling and freezing points of water on the Celsius and Fahrenheit scales.



10-4 SPECIFIC HEAT

One of the physical properties of matter is called **specific heat**. This is the number of calories of heat energy that must be added to 1 gram of a substance to raise its temperature 1 Celsius degree. Every substance has its own specific heat.

Because water is so common, all specific heats are compared with the specific heat of water. In Section 10-3 you learned that 1 calorie of heat energy will raise the temperature of 1 gram of water 1 Celsius degree. Hence, the specific heat of water is 1 calorie per gram per Celsius degree. Water has a high specific heat as compared with most other substances. For example, when the sun is shining on a beach, the water warms very slowly, whereas the sand becomes hot.

The metals used for making cooking utensils have low specific heats. Why is this an important characteristic? The specific heat for aluminum is 0.21; for copper, 0.09; and for iron, about 0.11. How fast will the temperature of an aluminum pot rise in comparison with an equal mass of water when the rate of flow of heat into each is the same?

10-5 HEAT OF VAPORIZATION

The addition of heat to a substance causes its molecules to move faster by giving them more kinetic energy. As the molecules move faster, the temperature of the substance rises. By definition, the specific heat of water is 1, so it takes 100 calories to raise the temperature of 1 gram of water from 0°C to 100°C.

Water does not boil as soon as it has absorbed enough heat energy to raise its temperature to 100°C. It must gain additional heat energy to make the molecules move fast enough to change from the liquid state to the gaseous state. The heat energy required to change matter from a liquid to a gas is called the **latent heat of vaporization**. The heat of vaporization of water varies slightly, depending on the starting temperature of the water. For liquid water at 100°C, about 539 calories of heat energy are required to change each gram of water to water vapor at the same temperature.

According to measurements made in the laboratory, it takes about 585 calories of heat energy to convert 1 gram of liquid water at the normal range of air temperature to water vapor (see note in margin). The added energy remains in the vapor. Only when the vapor is changed back to the liquid form will this latent heat of vaporization be released.

The colder the water is, the more heat energy is needed to produce water vapor (595 calories at 0°C; 585 calories at 20°C).

When you have been swimming and are lying in the sun, the water on your skin begins to evaporate. This water is being changed to water vapor without ever reaching the boiling point. You have observed other conditions when water becomes a vapor without boiling. All that is needed to cause evaporation is sufficient heat energy transferred to a molecule.

When water evaporates from your skin, you feel cooled. Part of the heat energy that causes the evaporation is transferred from your body to the water. This loss of heat from your body lowers the temperature of your skin.

The evaporation of water from the earth's surface adds a large amount of latent heat to the atmosphere. A summer shower deposits about 1,000 grams of water on each square meter of ground. Calculate how much latent heat energy is added to the atmosphere at 20°C as that small area dries by evaporation.

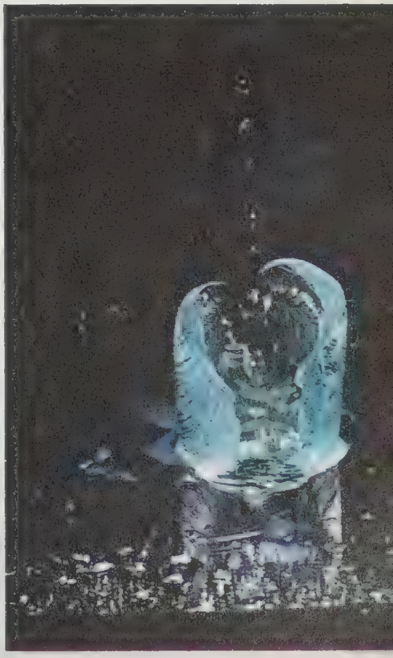


Figure 10-5 The three states of water—solid, liquid, and vapor

Study Guide

1. Why does you skin feel cool after you have been swimming?
2. Explain how evaporation occurs.
3. Define a calorie.
4. How does one measure the effect of heat energy on a substance?
5. In your own words, explain specific heat.
6. Why does it take 539 calories to change 1 gram of water at 100°C to steam?

10-6 WATER MOLECULES IN ACTION

Once liquid water has been converted to water vapor in the air, several things happen. We are interested in three of

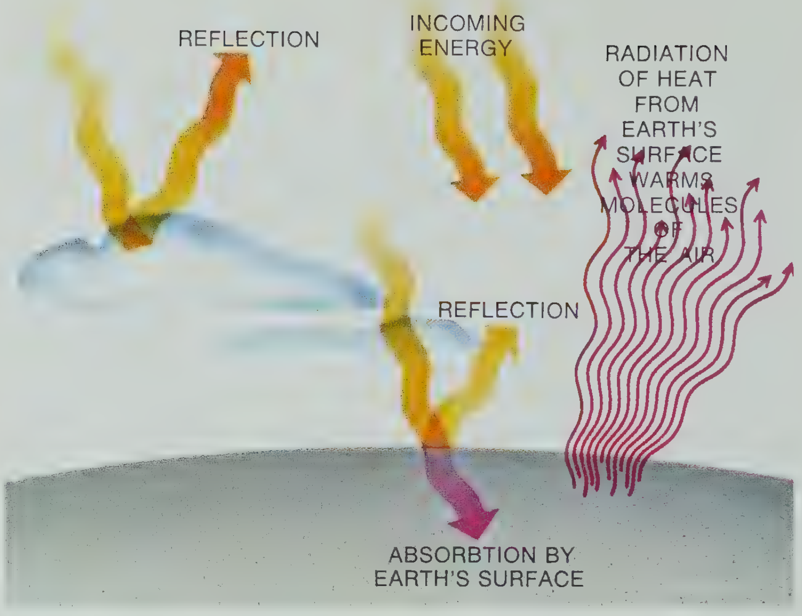


Figure 10-6 Much of the incoming solar radiation is absorbed by the surface of the earth, which converts it to long-wave heat energy. Molecules of the air, including water molecules, are warmed by this heat. The specific heat of water vapor is about twice that of oxygen or nitrogen. Therefore, moist air heats and cools more slowly than dry air.

Even a thimbleful of air contains more molecules than a billion times the number of people in the world. It is not surprising, therefore, that air molecules collide with one another.

these. First, the water-vapor molecules travel in straight lines until they collide with other gas molecules in the air. In a gas, the molecules are much farther apart than in a liquid or solid (see note in margin).

Molecules appear to be elastic. When they collide, they bounce away from each other, as two billiard balls or marbles do. In this way, the water molecules that escape from a water surface become scattered in the air. This spreading of one kind of gas molecule among others is called **diffusion**.

Second, the addition of water vapor to the air actually lowers the air's density. This occurs because water-vapor molecules have less mass than either the oxygen or the nitrogen molecules that make up about 99 percent of dry air. The addition of water vapor to air lowers the average molecular mass of air, therefore lowering its density. At the same temperature and pressure, moist air is lighter than an equal volume of dry air.

The third effect of evaporation occurs when air molecules absorb solar energy. Some of this energy is converted to heat. Air molecules can also absorb heat energy that is radiated from the surface of the earth, as shown in Figure 10-6.

The heat energy absorbed by air molecules makes them move more rapidly. The faster they move, the greater the

distance each one may travel in a given time. However, the increased movement of molecules will cause a greater number of collisions to occur in a given time. In a confined space—a sealed can, for example—the increased number of collisions increase the pressure on the walls of the can. In an open space, the collisions cause the molecules to become more scattered. Thus, air or any substance will expand into a greater volume as it is heated.

Since heated air expands, there are fewer molecules in a cubic meter of warm air than in a cubic meter of cool air. We can say that warm air is less dense (lighter) than cold air because the molecules are more widely spaced. Warm air that is surrounded by cool air tends to rise. The effect is the same with moist air surrounded by dry air, but the difference in density is not so great as that between warm and cool air.

The force that causes a fluid (or a solid object) to float or rise in a second fluid is called **buoyancy**. In the third century B.C. Archimedes discovered that the weight of a volume of fluid (or a solid) that is being held up by another fluid is equal to the force of buoyancy. The important factor in determining the buoyant force between two volumes of air is the difference in density between them. If warm, moist air continued to rise and never stopped, the earth would have lost all of its water and most of its air a long time ago. Obviously, the warm, moist air must stop rising somewhere.

10-7 A HIGH COLUMN OF GASES

The air near the surface of the earth is at the bottom of a sea of air that is well over 100 kilometers high. The weight, or pressure, of this column of gas squeezes the molecules of the

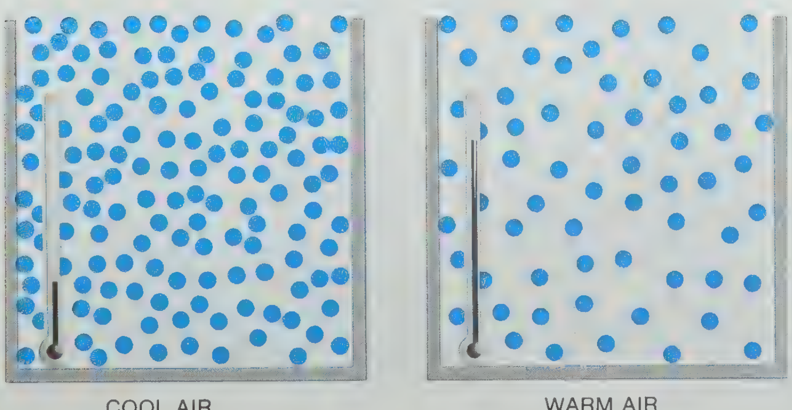


Figure 10-7 Because the molecules are spaced closer together in cold air, the density of cold air is greater than that of warm air.

At an altitude of 10 kilometers, the air pressure is only about 25 percent of that at sea level. The density of the air at 10 kilometers is about 30 percent of that at sea level.

lower air into less space. When you stand at the top of a high mountain, such as Pikes Peak (4.2 kilometers above sea level), about 40 percent of the air is below you. The air pressure is only 60 percent of that at sea level (see note in margin).

The less dense air in the upper atmosphere contains fewer molecules per unit volume than the air at the earth's surface. As a result, this lighter air can absorb less heat energy per unit volume than the denser air at the surface. Thus, the higher you go above the earth's surface, the cooler the temperature will be. However, this holds true only up to about 10 kilometers, where the average temperature is about −50°C (−58°F). Above this altitude, conditions change. These special conditions will be discussed in Chapter 12.

Air rising from the surface of the earth is progressively under less pressure, and thus it expands. In expanding, the molecules move farther apart, and the heat energy they contain is spread through a greater volume. The air temperature is lowered, even though each molecule contains the original amount of heat energy. Thus the air that rises from the surface of the sea or land is cooled. The relationship between air temperature and its volume is shown in Figure 10-8.

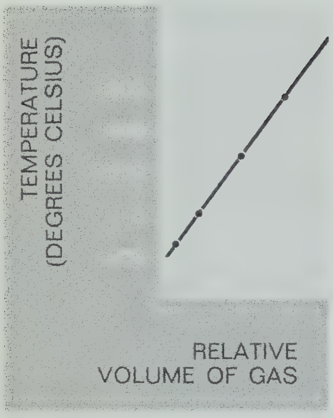


Figure 10-8 The temperature of a gas affects its volume.

Scientists use a special term to describe changes in temperature that occur without any heat energy being added or lost. These changes are called **adiabatic changes**. Thus, when air cools because it has expanded, the process is called **adiabatic cooling**. What is the process of heating called when it occurs because the air is compressed?

Study Guide

1. Explain how the diffusion of water vapor into the air takes place.
2. Why is warm air less dense than cool air?
3. Explain why cool air tends to sink.
4. What happens when the sun's rays strike water molecules?
5. Why does the temperature of a gas decrease when it expands?
6. From Figure 10-8, determine to what temperature a volume of gas must be heated to become 3 times its original volume.

10-8 WATER DROPLETS FROM WATER VAPOR

As moist air gets colder, its molecules lose kinetic energy and slow down. With this loss of kinetic energy, the water-vapor molecules do not rebound as much after a collision with other molecules. So much energy may be lost through cooling that another force causes the molecules to stick to each other.

Let us analyze the structure of a water molecule to help us understand why this happens. As shown in Figure 10-9, two hydrogen atoms are attached to the same side of an oxygen atom. The oxygen side of the molecule has a negative charge in comparison to the hydrogen side. Any molecule that has a charge near its ends is called a **polar molecule**.

When two water molecules have lost so much heat energy that their kinetic energy is weaker than their slight polar charges, they may cohere (stick together) when they collide. This happens to water-vapor molecules at low temperatures high in the atmosphere.

Just as the change from liquid to vapor has a name—evaporation—so the reverse action has a name—**condensation**. This reverse action occurs when the air can no longer hold the water vapor that is present. The vapor changes to a liquid. The amount of water vapor the air can hold depends almost entirely on the air temperature. As you can see from the data in Figure 10-10, the warmer the air, the more vapor it can hold. The **dew point** is the temperature at which moisture condenses; the more moisture in the air, the higher the dew point. At what time of day does dew usually form? Why?

The condensation of water vapor in the air depends also on how dirty the air is. The atmosphere is composed of more than just gases. Particles of dust, bacteria, pollen, salt from the ocean surfaces, and other small fragments of solids are found throughout the atmosphere. Some of these particles attract water molecules because of their chemical makeup or because of their electrical charges (see Figure 10-11). Remember, water is a polar molecule. Salt is also a polar particle.

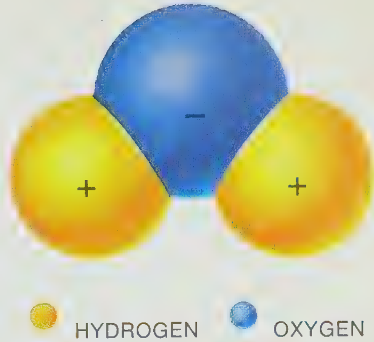


Figure 10-9 Water molecules are electrically charged.

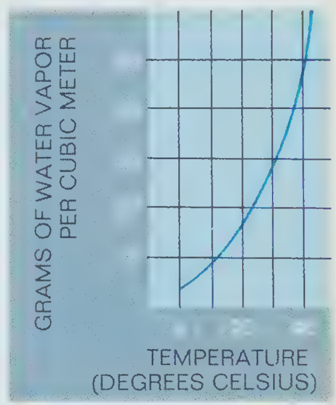


Figure 10-10 The vapor capacity of air is regulated by temperature.

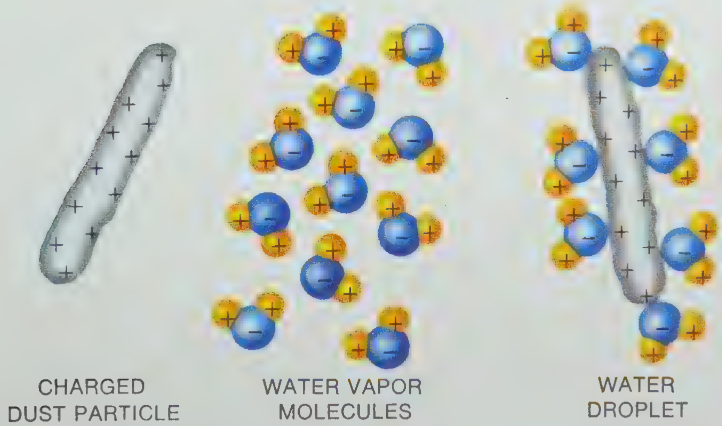


Figure 10-11 Microscopic salt particles thrown up by the churning of the ocean surfaces are carried high into the atmosphere by air currents (see the photograph at the beginning of this chapter). There these particles attract molecules of water vapor and provide a surface on which they may condense.

The condensation of water vapor in the air would not take place as readily as it does if the air were pure and free from particles. These particles are called **nuclei of condensation**. As water vapor condenses to liquid on the surface of one of these nuclei, a microscopic (0.005 to 0.050 millimeter in diameter) water droplet is formed. If a large number of these water droplets become visible, we call the formation a **cloud**.

In Section 10-5 you learned that it takes energy in the form of latent heat of vaporization to change water to water vapor. What happens to that latent heat when condensation takes place? The energy must be released or the water vapor will never condense. This energy is called the **latent heat of condensation** and is equal to the latent heat of vaporization for the same amount of water.

10-9 MEASURING THE WATER VAPOR IN THE AIR

Water can occur in the air in three forms—vapor, liquid, and solid (ice or snow) (see Figure 10-5). We are particularly interested in the water vapor, or **humidity**, and whether it will cause rain or snow. How does a meteorologist predict when water vapor will condense?

Grams per cubic meter is the unit of the metric system used to measure the air's moisture-holding capacity. In the English system, grains per cubic foot is the unit.

The amount of water vapor in the air depends on two factors—the amount of water available for evaporation and the air temperature. You can see in Figure 10-10 that the higher the air temperature, the more water vapor the air can hold. For each degree of temperature, there is a saturation point—that is, the maximum amount of water vapor the air can hold.

The actual amount of water vapor in the air is called the **absolute humidity**. This measurement alone does not indicate how likely it is that rain or snow will occur. We must also know the temperature of the air. A measurement that includes the temperature factor is the **relative humidity**, which is an indication of how close the air is to being filled to capacity with water vapor. The lower the temperature, the higher the relative humidity. For example, a sample of air at 21°C (70°F) might have a relative humidity of 27 percent. At 4°C (40°F) it would have a relative humidity of 76 percent. The relative humidity is given in percent. The equation for calculating relative humidity is:

$$\text{Relative humidity} = \frac{\text{Absolute humidity}}{\text{Capacity}} \times 100$$

The closer the measurement is to 100 percent, the closer the air is to being filled to capacity.

Another measurement used to predict rain or snow is the dew point. If it is not raining or snowing, the dew point must always be equal to or less than the air temperature. As soon as the air temperature drops below the dew point, condensation begins.

Figure 10-10 shows that air at 30°C can contain only 29.9 grams per cubic meter of water vapor before condensation will occur. Air at 20°C can contain only 17.3 grams per cubic meter (see question in margin).

Suppose a particular mass of air at 30°C contained 25 grams of water vapor per cubic meter. What would happen if the temperature of the mass of air dropped to 20°C? Calculate the relative humidity of the mass of air at 30°C.

The dew point is a clue to relative humidity. If the air temperature and the dew point are close, then the relative humidity is high. If the two temperatures are far apart, the relative humidity is low.

10-10 THE FORMATION OF RAIN

Water vapor that has condensed into clouds returns to the earth's surface as precipitation. How does this happen? Scientists have concluded that there are at least two processes by which a cloud can release its liquid water as rain or snow.

The first of these processes is called **coalescence**. The microscopic water droplets that make up a cloud are light enough to be supported by rising air currents. These droplets may fall for short distances, but friction between the droplets and the rising air will carry them back up again.

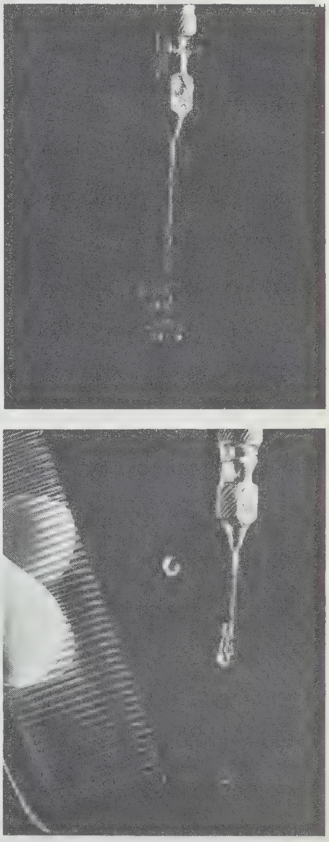


Figure 10-12 The formation of water droplets by coalescence. The comb, charged with static electricity, causes the water droplets to combine into one large drop.

In the presence of electrical charges colliding water droplets stick together, or coalesce, as shown in Figure 10-12. The new droplet is larger and heavier than the original ones. Thus, it is more likely to collide with a third droplet as it falls and rises. In time, the droplet will grow to raindrop size, somewhere between 0.1 and 6.0 millimeters in diameter. The weight of the drop will be strong enough to overcome the force of the rising air currents, and the drop will fall to the earth.

The other process that results in precipitation is called the **ice-crystal process**. This is based on the assumption that the temperature near the top of all rain clouds is below freezing. Some of the water vapor will condense and freeze into ice crystals. These crystals will be surrounded by droplets of water that have not yet frozen. These are called **supercooled** water droplets.

The supercooled water has a tendency to condense and freeze on the surface of nearby ice crystals. Also, the super-

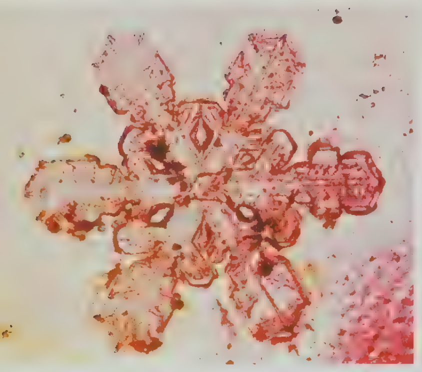


Figure 10-13 Ice crystals are always hexagonal—six-sided—but occur in an infinite variety of patterns.

cooled water will freeze immediately if it is disturbed, as by the collision with an ice crystal. The ice crystals are beautiful six-sided shapes, as shown in Figure 10-13.

The growing ice particles fall when they overcome the force of the rising air currents. ~~If the~~ temperature of the air ~~above the ground is near~~ or below ~~freezing, snow will result.~~ If the falling crystals melt before they hit the ground, rain results. ~~Many meteorologists~~ believe ~~both of~~ these processes must be used to explain the formation of rain and snow.

10-11 ENERGY IN RAIN

We have seen that precipitation is produced from water vapor that has risen high enough to condense and form a cloud. When condensation occurs, the latent heat energy that caused evaporation is released. Stored within the droplets and then in the raindrops is the potential energy gained when the water vapor rose from the earth's surface to where it condensed.

Once a raindrop has started to fall to the earth, its potential energy is converted to kinetic energy—the energy of motion. Not all the potential energy is changed at one time. If raindrops land anywhere higher than the level of the oceans, they retain some potential energy. The amount of potential energy depends on the mass of the drop and on the vertical distance it must still fall to reach sea level. Thus, rain that falls on a high mountain retains more potential energy than rain that falls on the lowlands.

Study Guide

1. From Figure 10-10, find the difference in the water-vapor capacity of air between 15°C and 30°C.
2. Why do water molecules tend to cling together?
3. How do particles of dust and salt in the air help raindrops to form?
4. Why does a glass filled with ice water sometimes become covered with water droplets on the outside?
5. Why do water droplets not fall to the ground as soon as they are formed in a cloud?
6. How much heat will be released when 1 gram of water vapor at 20°C changes to water droplets at that temperature? (See Section 10-5.)

SUMMARY

Moving water erodes soil, transports the load it carries, and deposits it on the earth's surface. Energy is involved in all these actions. The

energy available to the water in streams is the potential energy that remains in rain after it has reached the ground. The ultimate source of the energy in all forms of water is the sun.

Water enters the atmosphere by means of evaporation. When water vapor condenses to form liquid water, the latent energy is released in the form of heat. Since the water molecule is lighter than either the oxygen or the nitrogen molecules, air containing water vapor is slightly less dense than dry air at the same temperature. Warm air expands. This causes it to be less dense than cool air. Warm, moist air tends to rise when surrounded by cool, dry air.

The amount of water vapor that air can contain is related to the temperature of the air. Changes in temperature, therefore, affect the formation of clouds, which are masses of water droplets. The presence of tiny solid particles aids the development of water droplets. When raindrops or ice crystals grow heavy enough, they fall.

REVIEW AND DISCUSSION QUESTIONS

1. When water boils, it is changed from the liquid state to the vaporous, or gaseous, state. Why does this change of state also occur at temperatures below the boiling point?
2. Very often when you have been swimming outdoors in the summer, you become chilled when you come out of the water. Explain why this occurs.
3. Water is composed of one oxygen and two hydrogen atoms, and it is polar. Carbon dioxide is composed of one carbon atom and two oxygen atoms, and it is nonpolar. Using what you have learned about the water molecule, describe how you believe the carbon dioxide molecule must be built.
4. Scientists believe that only 20 to 25 percent of the water that falls from clouds ultimately reaches the oceans. What may happen to the rest of the water?
5. It is often observed that during a snowstorm or rainstorm the temperature rises. Account for this.
6. Usually the air feels cooler after a summer shower. Why?
7. Trace the path of solar energy during the hydrologic cycle.
8. In fruit-growing areas, late-spring killing frosts can ruin an entire crop. When killing-frost warnings are sounded, the orchardmen light smudge pots, which put a layer of smoke over the orchard. If there is little or no wind with the freezing weather, this precaution often saves the crop. Explain how a layer of smoke can help the crop.
9. The contents of a spray can, such as hair spray or deodorant, feel cold as they leave the nozzle. Why?
10. Often it can snow when the temperature is above freezing. Also, it may rain when the temperature is below freezing. Why?

CHAPTER **11**

THE EARTH IN MOTION

In Chapter 10 it was mentioned that the wind moves clouds. To understand why this occurs, it is necessary to turn our attention from the hydrologic cycle in order to learn something about winds. There are two fundamental causes of wind—the uneven heating of the earth's surface by solar energy and the rotation of the earth on its axis. Let us see what we already know about the earth's movements from our own experience. Such simple observations were the starting points for many early scientific investigations.

We know that day and night continuously follow one after the other. The length of daylight in 24 hours at any one place slowly changes during the year. In the Northern Hemisphere the change is from the least daylight in December to the greatest in June. We know that the position of the sun in the sky at noon changes during the year. It is nearest to being directly overhead (nearest the zenith) at noon during June and farthest from the zenith at noon in December. Daily temperatures are highest in summer and lowest in winter. Much of this we take for granted. Let us try to find explanations for all these observations.

11-1 EARTH'S ADDRESSES

For our study of the earth's movements we shall need a set of references that will enable us to locate a specific spot on the earth's surface. The early Greek map makers, living about 400 B.C., realized this. They devised a set of parallel lines running east and west, and another set running north and south. These lines divided the maps into many small rectangles. They thought that the earth was flat and that it was wider east to west than it was north to south (see the map, Figure 11-1). They called the east-west lines **latitude**. The north-south lines were called **longitude**. We still use these names in the same way, although we apply them to a spherical earth.

The earth as seen from near the moon

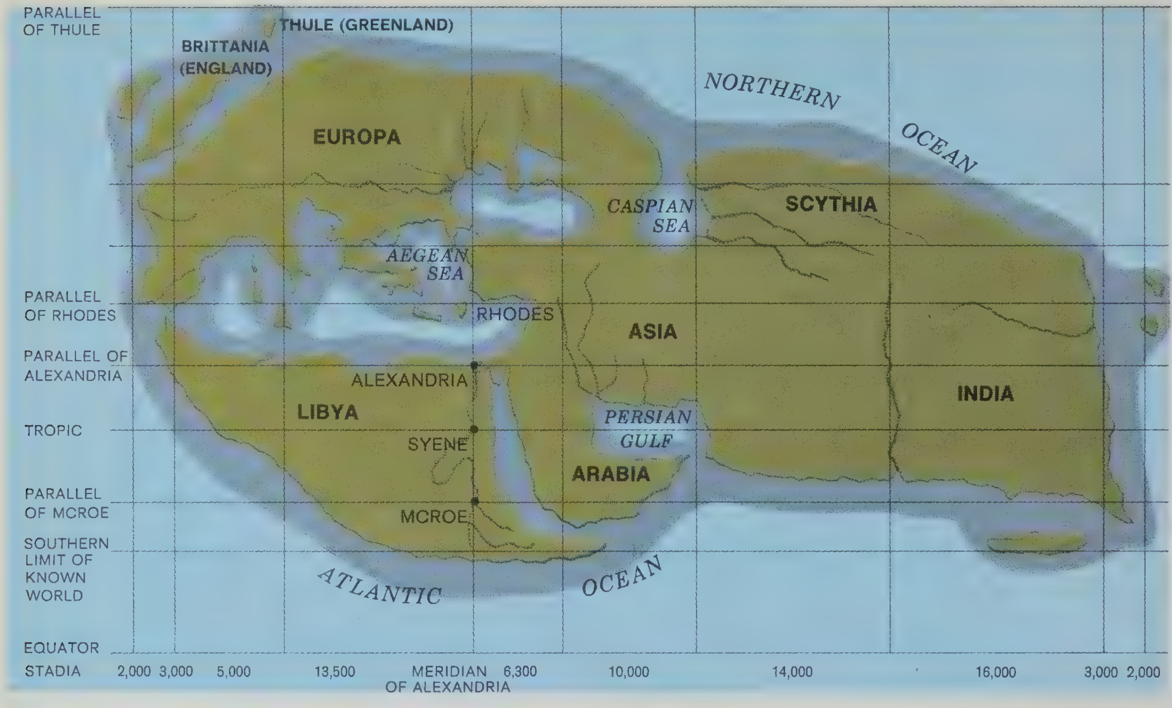


Figure 11-1 The starting point for the Greeks was Greece, which they thought was the center of the earth. Distances were measured in *stadia* (singular, *stadion*). A stadion is equal to about 607 feet.

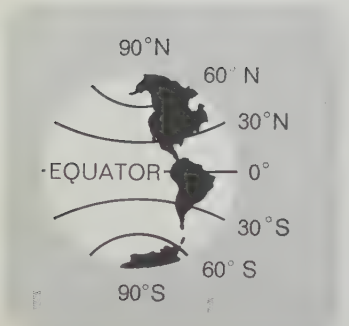


Figure 11-2 Parallels of latitude are imaginary lines running east and west around the earth. They represent the angular distances north and south of the equator measured through 90°. With a protractor, determine where the parallel of 10°N is.

The Greek map makers identified these imaginary lines on their maps with numbers based on distances from a starting place. Today latitude and longitude are measured in number of degrees away from a reference line.

The modern reference line for the east-west lines of latitude is the equator. Latitude lines indicate distance north and south of the equator. Since latitude lines are all parallel with the equator, they are referred to as the **parallels of latitude** (see Figure 11-2).

Our reference for longitude is a line that passes through the Royal Astronomical Observatory, in Greenwich, England. This line is called the **prime meridian.** Read the sign in Figure 11-3.

Each line of longitude passes through the North and South Poles and is perpendicular to the equator. Longitude lines indicate distance east and west of Greenwich. The lines of longitude are not parallel to each other but converge as they approach the Poles, as shown in Figure 11-4. Each line of

longitude moves directly under the sun at noon for that longitude. The name for these lines is **meridians**.

The parallels are numbered from 0° at the equator to 90° north (N) at the North Pole and 90° south (S) at the South Pole. The meridians are numbered in degrees east (E) or west (W) from 0° at Greenwich to 180° in the Pacific Ocean.

To understand why is simple. Any circle, such as a flat outline of the earth, contains 360 degrees. This is an arbitrary number set by man. In the case of latitude, the farthest away from the equator you can go is one quarter of the way around the world. If you were to continue past the Poles, you would be getting closer to the equator. One fourth of 360 degrees is 90 degrees.

In measuring longitude, the farthest away from the prime meridian you can go in an east or west direction is halfway around the world. One half of 360 degrees is 180 degrees.

Each degree is divided into 60 minutes, written as 60′. A minute is further divided into 60 seconds, written as 60″. By using the number of degrees from the equator and from the prime meridian, any place on the earth's surface can be located and given a precise reference, or "address" (see note in margin).

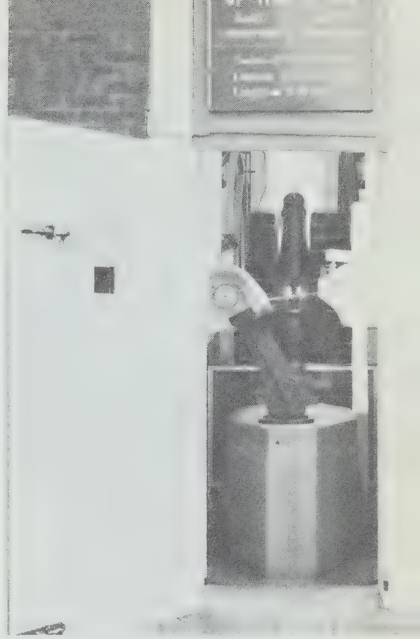


Figure 11-3 This is the reference point, the prime meridian, or 0 degrees longitude, from which lines of longitude are computed.

11-2 DETERMINING LATITUDE

The latitude of any place can be found by observing the stars. In the Northern Hemisphere you can approximate the latitude for your home on any clear night. The North Star, Polaris, at the end of the "handle" of the Little Dipper is always almost directly over the North Pole. In the Northern Hemisphere you can get an estimate of your latitude by measuring the angle formed by the North Star, yourself, and the horizon

For instance, the National Bureau of Standards, in Washington, D.C., is located at 38°56′18″N; 77°4′0″W. This is read as 38 degrees, 56 minutes, 18 seconds north latitude; 77 degrees, 4 minutes, 0 seconds west longitude.

Figure 11-4 Lines of longitude, unlike parallels of latitude, run north and south from the Poles and are perpendicular to the equator.

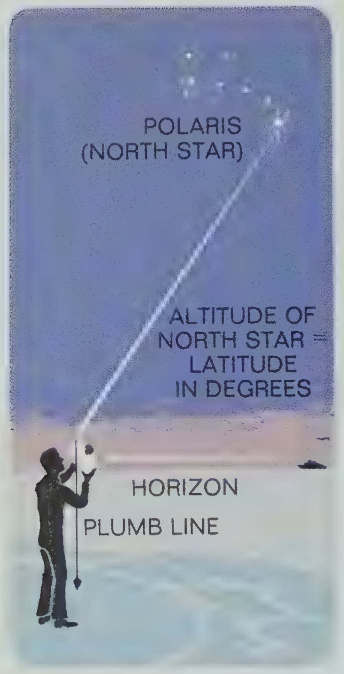


Figure 11-5 One way to calculate latitude. Polaris determines one side of the angle, and the ship on the horizon determines the other side. Latitude can be approximated by measuring the angle formed by these two sides. Why is it necessary to have a clear, flat horizon in order to do this with fair accuracy?

Figure 11-6 A sextant is used in computing the altitude of a celestial body. The sun, the moon, or any of the stars can be used for fixing, or determining, the latitude of a place. However, using any celestial body, including the North Star, requires complicated calculation and tables of value.

directly below the North Star. Figure 11-5 illustrates a practical way of measuring the angle, or **altitude**, of a star.

For locating the latitude of a place very precisely, carefully built instruments are used. Surveyors use a theodolite, or transit, and navigators on ships or aircraft use a sextant.

11-3 THE PROBLEM OF LONGITUDE

In fixing the latitude of a place on the earth, one makes use of two natural points on the earth's surface—the equator and a Pole. Longitude, however, is not based on a natural position but on an arbitrary one, the prime meridian.

The story of the prime meridian goes back to the seventeenth century. British vessels were raiding and capturing the Spanish vessels transporting gold and silver from South America to Spain. To do so without first touching upon the American coasts, British navigators needed a sure way of determining longitude at sea. Sir Isaac Newton suggested that this could be done if someone could invent an accurate clock that did not require a pendulum to regulate it (see note in margin).

At that time, a pendulum clock was the only kind that kept accurate time. At sea, however, the motion of the vessel disturbed the swing of the pendulum. In the fifteenth century, Walther of Nuremberg had invented a clock in which a spring drove a set of cogwheels but it was inaccurate.

In 1714 the British government offered a prize of £20,000 for the invention of a method by which ships could be navigated to the West Indies with an error of less than 30 miles.

In 1736 a Yorkshire carpenter, John Harrison, improved the spring-driven clock, enabling navigators to keep accurate time at sea in all kinds of weather. Harrison's **chronometer**, as it was called, made possible the accurate determination of longitude. British vessels then began to measure longitude from the Royal Astronomical Observatory at Greenwich, near London, and we still do today.

To determine the longitude of a place, we take advantage of the fact that the sun appears to pass around the earth from east to west once every 24 hours. This means that the sun appears to travel the 360 degrees of longitude each day. In one hour it would appear to pass 15 degrees of longitude. Why? Figure 11-7 should help.

Getting a fair determination of longitude requires an accurate clock, or chronometer. The chronometer shows the time at the prime meridian, called Greenwich Mean Time (GMT). The GMT is then noted for the instant the sun crosses the meridian you are upon. The difference between GMT and your time allows you to calculate the longitude of your meridian. For example: At noon, when the sun crosses an unknown longitude, the prime meridian time reads 1 P.M. This means that the difference in time between the prime meridian and your longitude is one hour. How many degrees does the sun appear to travel in one hour? (15 degrees.) Therefore, your longitude is 15 degrees west of the prime meridian. Since determining longitude involves time, we should investigate that phenomenon.

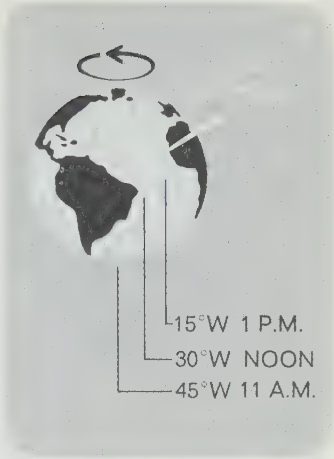


Figure 11-7 Longitude is much more difficult to compute than latitude. One must measure local time at a given place and compare it with Greenwich Mean Time.

Suppose the prime meridian chronometer reads 11 A.M. when it is noon where you are. What would be your longitude?

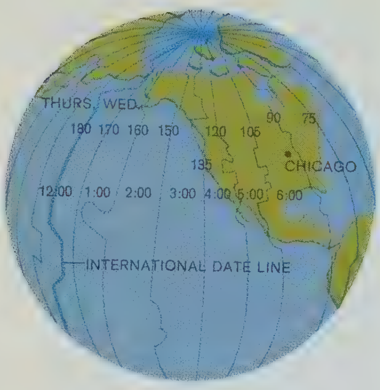
Study Guide

1. What natural positions on the earth is latitude based on?
2. Explain why lines of latitude are referred to as parallels of latitude.
3. Why are there only 90 degrees of latitude?
4. What is the latitude of the North Pole?
5. Over which meridian should the sun be exactly two hours after it has crossed the prime meridian?

11-4 TIME

In Section 3-3 it was stated that there are only two natural divisions of time—the day and the year. We use smaller, man-made divisions of these units every day of our lives. What are those divisions? We divide the day into halves, which we label A.M. and P.M. Both these 12-hour periods are related to the position of the sun in respect to a meridian (see note in margin).

A.M. is an abbreviation of the Latin *ante meridiem*. The Latin word *ante* means "before." When we use A.M., we mean that the sun has not yet reached our meridian. The Latin word *post* means "after," so what does P.M. (*post meridiem*) mean?



Figute 11-8 The standard time zones

Suppose we used the sun's crossing of a meridian as the signal for midday, twelve noon. Practically every town in the United States would have a different time showing on its clocks. As a matter of fact, this actually was the case only a hundred years ago.

With every city and town going on its own time, no great harm was done so long as the fastest way to travel was by horse and buggy. But when railroads began crossing the country, this situation became difficult. In 1880 the United States was divided into four **standard time zones**—each about 15 degrees of longitude wide. Figure 11-8 shows some of the earth's time zones. Why do these zones have an average width of 15 degrees? Since each 15 degrees of longitude represents one hour, you can see why you must change your watch when you travel long distances east or west.

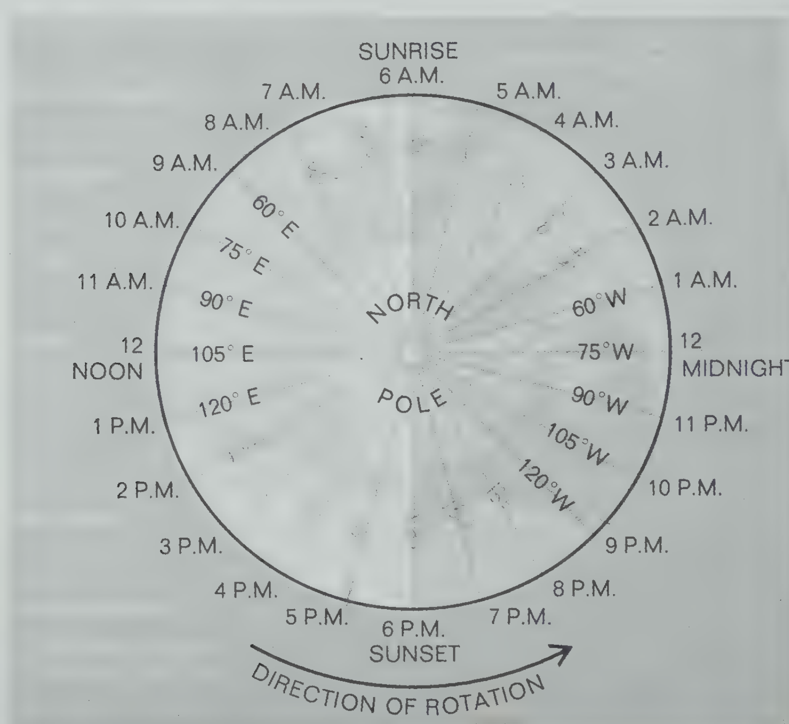


Figure 11-9 As a person crosses the international date line, the date and the day name change. For example, on Monday the 10th you leave San Francisco, flying west. When you cross the date line, it is Tuesday the 11th. However, if you left Japan on Thursday the 13th, flying east, it would be Wednesday the 12th when you crossed the date line.

The central meridian for the Eastern Standard Time Zone is the 75th west meridian, or 75°W longitude. Only those places situated exactly on that meridian show noon on their clocks very close to the time when the sun crosses the meridian (see note in margin).

This is true in all our time zones – Eastern, Central, Mountain, Pacific, and so on. What is the time meridian for your time zone? Notice that each time meridian is a multiple of 15. Why?

Clock time moves from east to west. Look at Figure 11-9, which represents the arrangement of meridians viewed from over the North Pole. Notice that when it is noon Eastern Standard Time on the 75th west meridian, it is one hour earlier, 11 A.M. Central Standard Time, on the 90th west meridian. In one hour it will be 1 P.M. Eastern Standard Time and noon Central Standard Time. That is, the sun will appear to have moved 15 degrees westward. San Francisco uses the 120th west meridian as its time meridian. What time is it Pacific Standard Time when it is 10 A.M. Eastern Standard Time?

When does one day end and the next day begin? The most convenient time for us is midnight, so that is when we make the change.

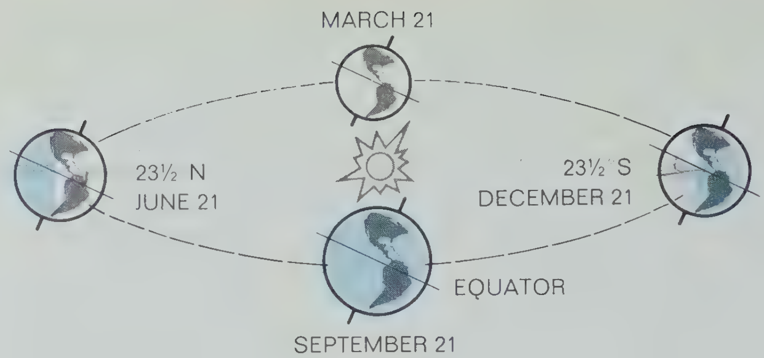
Where does a new day begin? It could begin at any meridian. It might seem logical to start at the prime meridian (0°). But that is in a very densely populated area and would be too inconvenient. England and Spain would be one day ahead of the rest of Europe. The 180th meridian lies almost entirely over the Pacific Ocean, where there are very few people to be inconvenienced. Therefore, we start a new day on the sun's apparent westward trip around the earth at the 180th meridian. This meridian is called the **international date line**.

11-5 THE SEASONS

The time it takes for the earth to make one complete journey around the sun is called a year. It is 365.24 twenty-four-hour days long. During that time, we in the United States pass through the four seasons – winter, spring, summer, and fall. Why do we have seasons? The earth's axis of rotation is tilted, or inclined, to the plane of the earth's orbit around the sun. This tilt is called the **inclination** of the earth. The north end of the axis points in the same direction all the time – almost directly to the North Star.

On June 21 the Northern Hemisphere is tilted $23\frac{1}{2}$ degrees toward the sun, as shown in Figure 11-10. This makes the sun appear to be directly overhead at noon at $23\frac{1}{2}$°N (or 23°30′) latitude. That is as far north as the sun ever is directly overhead (at the zenith) at noon.

Figure 11-10 Four positions of the earth in its orbit around the sun. Would there be seasons if the earth's axis were perpendicular to its orbit around the sun? During which months are daytime and nighttime about equal?



If on June 21 we could see the stars surrounding the sun, the sun would appear to be among the stars of the Crab (Cancer) constellation. Because of this, the 23½°N parallel is called the Tropic of Cancer. On December 21 the sun appears to be among the stars of the Goat (Capricorn) constellation. What special name is given to the 23½°S parallel?

After six months have passed, on December 21, the sun appears at the zenith at 23½°S latitude. In other words, the Southern Hemisphere is tilted toward the sun. Thus, the sun appears to travel 47 degrees southward between June 21 and December 21, and 47 degrees northward during the next six months. The effect of this apparent north and south traveling of the noon position of the sun causes the seasons (see comment in margin).

Summer begins in the Northern Hemisphere on about June 21, when the Northern Hemisphere receives its maximum radiation from the sun. At this time the Southern Hemisphere is receiving its minimum radiation, and winter is beginning there. When winter begins, on about December 21, in the Northern Hemisphere, summer is beginning in the Southern Hemisphere.

In Figure 11-10 the earth and sun relationship is also shown for March 21 and September 22. On these two days the sun appears at the zenith at noon directly over the equator. Then there are exactly 12 hours of daylight and 12 hours of darkness everywhere in the world. These two days are called the **equinoxes**, a Latin word meaning "equal nights." March 21 is the **vernal equinox** and September 22 is the **autumnal equinox**.

solstice (SOL stis); Latin: *sol*, sun + *sistere*, to stand still.

The two days when the sun is at the zenith 23½° north or south of the equator are called the **solstices.** June 21 is the **summer solstice** and December 21 is the **winter solstice.**

11-6 THE SEASONS AND SOLAR ENERGY

The major difference between summer and winter is the temperature. This, in turn, has its effect on the weather. Why

is it warmer in summer than in winter? Is it because the earth's path comes closer to the sun in summer? It does not. We are about 2 million miles farther from the sun during our summer than we are during our Northern Hemisphere winter.

What does have a marked effect is the angle at which the sun's rays strike the surface of the earth. At noon on June 21 the sun appears as high in the sky as it ever does in the Northern Hemisphere. If we were at the Tropic of Cancer at that time, a beam of sunlight one meter square would illuminate precisely one square meter of horizontal ground (see Figure 11-11).

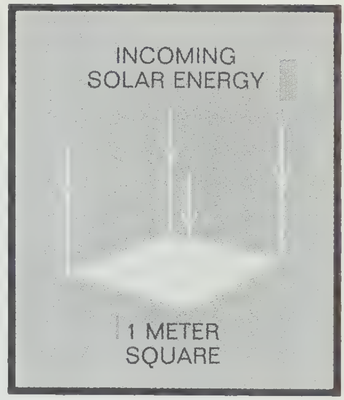


Figure 11-11 Between $23\frac{1}{2}$°N and $23\frac{1}{2}$°S, the sun is directly overhead at noon at some time during the year.

At that time a flagpole on the Tropic of Cancer would cast no shadow. Each square meter of horizontal ground would receive 19,200 calories of energy from the sun each minute, if there were no atmosphere to interfere. This much **in**coming **sol**ar radi**ation**, or **insolation**, is enough energy to light twelve 100-watt electric light bulbs.

Six months later, at noon on December 21, the sun is at the zenith at the Tropic of Capricorn. The sun appears to have traveled southward 47 degrees ($23\frac{1}{2} + 23\frac{1}{2}$). A sunbeam now strikes horizontal ground at the Tropic of Cancer 47 degrees away from the perpendicular, as shown in Figure 11-12. Because of this, the incoming energy from a one-meter-square sunbeam is spread over more than one square meter. Why? Since the energy (19,200 calories) is spread over more area, that area is warmed less than it was by the zenith sun on June 21. Only two thirds as much solar radiation falls on any area on December 21 as falls on an equal area on June 21 at the Tropic of Cancer. Your laboratory manual shows you how to estimate the amount of insolation being received at any latitude at noon on any day of the year.

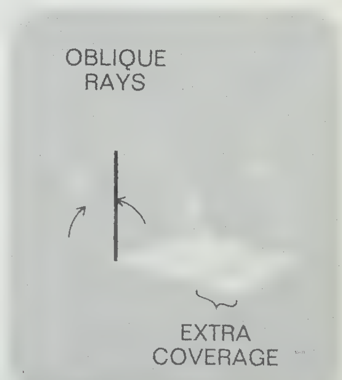


Figure 11-12 Oblique sunrays do not heat the earth as much as vertical sunrays do.

Study Guide

1. Explain why it became necessary to divide the earth into time zones.
2. How many degrees is the earth's axis of rotation tilted to the plane of orbit around the sun?
3. Toward what star does the north axis of rotation always point?
4. During the northern summer, how far north does the sun reach the zenith at noon?
5. How long does it take for the sun to appear to travel from the Tropic of Cancer to the Tropic of Capricorn?
6. When the sun is at the zenith at the Tropic of Capricorn, at what angle do the sun's rays at noon strike the Tropic of Cancer?

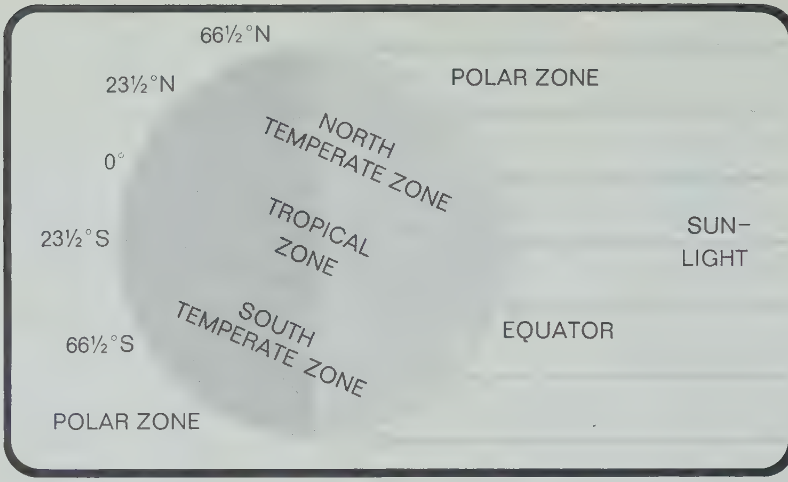


Figure 11-13 The position of the earth in its orbit on June 21

11-7 THE TEMPERATURE ZONES OF THE EARTH

During the summer, there is a region in the Northern Hemisphere where the sun does not set. At the North Pole, the sun does not go below the horizon between March 21 and September 22. At the southernmost parallel of this region, the sun does not set only on the day of the summer solstice. In between the North Pole and this southernmost parallel, the number of nightless days increases as you go north. This southern parallel is $23\frac{1}{2}$ degrees south of the Pole (see Figure 11-13). What is the parallel called?

The regions where on at least one day of the year the sun never sets are called by geographers the **Polar Zones**. The latitude that marks the equatorward edges of these zones is called the **Arctic Circle** in the north, and the **Antarctic Circle** in the south.

You have learned that there is a region on the earth where on at least one day of the year the sun reaches the zenith at noon. This is the **Tropical Zone**. What is the latitude that marks its northern limit? Where is its southern limit?

North and south of the Tropical Zone are large regions where the sun never reaches the zenith and where the sun shines every day (except, of course, on those days when clouds obscure it from our sight). These are the regions of the **Temperate Zones**.

11-8 SUNRISE AND SUNSET

We always think of the sun as rising in the east and setting in the west. The precise compass directions of the rising and

setting sun vary considerably during the year. In the Northern Hemisphere the sun rises to the north of east and sets to the north of west from late March until late September. During that period, there is more daylight than darkness.

For the rest of the year the sun rises and sets to the south of east or west. Sunrise and sunset are farthest north of east and west around June 21 and farthest south of east and west around December 21. The longest day is about June 21. What is the shortest day? Why?

11-9 THE POLESTAR CHANGES

Because of its tilt, the moon and the sun exert changing gravitational attractions on the earth. The axis of the earth undergoes an interesting motion. The movement is very similar to the slow wobble of a top spinning at an angle, as shown in Figure 11-14. The earth's axis traces an imaginary circle in the sky in about 26,000 years. The motion, called **precession**, changes the point in the heavens that is directly over the North Pole.

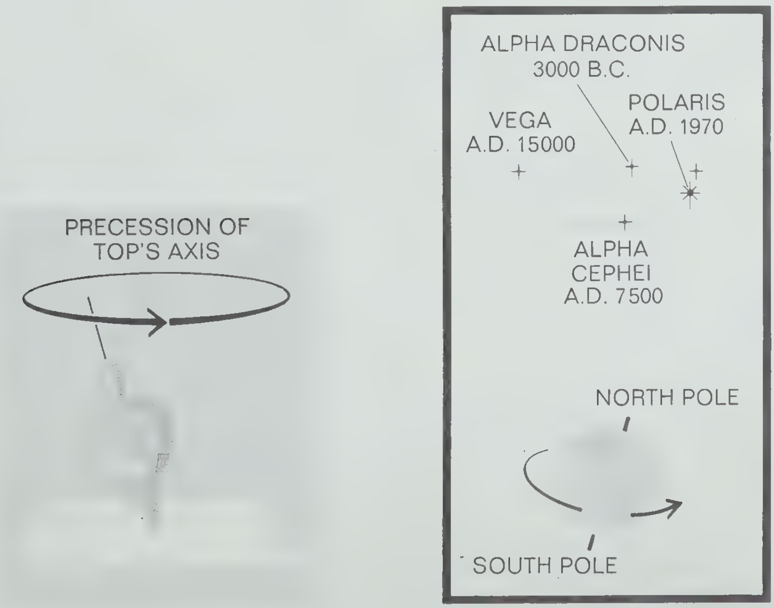


Figure 11-14 The wobble of a spinning top is a form of precession. About 5,000 years ago. Egyptian astronomer-priests recorded that the polestar was the star known as Alpha Draconis rather than the North Star. The axis of the earth appears to describe a circle in the sky with a radius of $23\frac{1}{2}°$ – the angle of the earth's tilt.

Although precession does not change the duration of seasons, it does have an effect on them. It causes the solstices (June 21 and December 21) and equinoxes (March 21 and September 22) to move through the year very slowly—a full cycle in 26,000 years. Therefore, in 13,000 years, winter will occur in what are now the months of summer.

Study Guide

1. What is the latitude of the Arctic Circle?
2. Describe the position of the sun as it would be seen at the Arctic Circle on June 21 at midnight.
3. What are the limits of the Temperate Zones?
4. When does the sun rise north of east in the Northern Hemisphere? At this time, where is the sun rising in the Southern Hemisphere?
5. Why was the polestar another star about 5,000 years ago?

SUMMARY

The equator is the reference point for latitude. The prime meridian, through Greenwich, England, is the reference point for longitude. Latitude is determined by celestial bodies. Longitude is determined by time differences. If it were not for standard time zones, every town would show a different time.

The available energy at the earth's surface comes almost entirely from the sun. The duration of sunlight and the angle at which the sun's rays strike the earth's surface vary. Therefore, the amount of energy received at a particular place varies through the year.

The inclination of the axis is responsible for the temperature zones and for the duration of each of the four seasons. The inclination is also responsible for the seasonal changes in the length of daylight and night and for the time and location of the rising and setting of the sun.

REVIEW AND DISCUSSION QUESTIONS

1. Imagine the earth with its axis tilted 45 degrees from the vertical instead of $23\frac{1}{2}$ degrees. Where would this place the Tropic of Cancer and the Tropic of Capricorn? How would this affect the climate in the United States?
2. We have learned that the equator and the Poles are natural reference points. How is their relation to the rotation of the earth important in making them reference points?
3. Using 8,000 miles as the diameter of the earth, calculate in miles and kilometers the distance between two degrees of latitude on the equator. Will this distance be the same between every two degrees of latitude? Why?

4. Explain why the distance in miles between two degrees of longitude cannot be calculated unless the latitude is known.
5. Why do areas near the equator not experience distinct seasonal changes?
6. Using the list of longitudes given below, calculate the time of day in each of the cities when it is twelve noon in Greenwich.

City	*Longitude*
Moscow	37°E
New York	73°W
Chicago	87°W
Denver	105°W
Los Angeles	118°W
Hong Kong	114°E

7. Why are the constellations seen in the summer sky different from those seen at the same spot in the winter sky?
8. The international date line is not a straight line on the earth. Why?
9. The longest day of the year in the United States has about 15 hours of daylight and 9 hours of darkness. The shortest day is just about the opposite. What are the reasons for this change in the length of the day during the year?
10. No matter where you live in the United States, your shadow will extend northward at noon. In what compass direction will a person's shadow extend at noon at the following places?
    a. The Tropic of Capricorn on June 21
    b. The equator on March 21
    c. The South Pole on December 21
    d. The North Pole on December 21

CHAPTER 12

SOLAR ENERGY AND THE ATMOSPHERE

We have seen how the spherical shape of the earth and the tilt of its axis of rotation affect the angle at which the sun's rays strike the earth. The angle that the sun's rays make with a flat surface is measured from a line perpendicular to that surface, and is called the **zenith angle**. At some latitude every day of the year the sun is at the zenith angle of 0 degrees at noon—that is, it is directly overhead. Also, at some latitude every day of the year the sun is no higher than the horizon, where the zenith angle is 90 degrees. Therefore, the amount of energy received at any one place varies a little from day to day. Let us investigate the effects of this energy.

12-1 THE ATMOSPHERE

In Section 11-6 we discussed incoming solar radiation as though the earth had no atmosphere. To reach the surface of the earth, the sun's radiant energy travels about 93 million miles through space. Then the energy enters a blanket of gases that surrounds the earth. As we have seen, the air is a mixture of gases. About one fifth of the air is oxygen, and about four fifths is nitrogen. There are also small amounts of other gases, including water vapor and carbon dioxide.

The atmosphere differs from the solid earth—the lithosphere—in a very important way. The matter that composes the atmosphere is made up of molecules that are widely separated as compared with the molecules in a liquid such as water or a solid such as rock. Figure 12-1 compares a gas with a liquid. From this example, you can see that the molecules of water vapor (a gas) must be much farther apart than those of water (a liquid).

What has all this to do with the earth and the amount of solar energy that comes to it? A great deal. Solar energy must

A unit called a langley (ly) is equal to 1 calorie per square centimeter and was named after Samuel P. Langley (1834-1906) of the Smithsonian Institution.

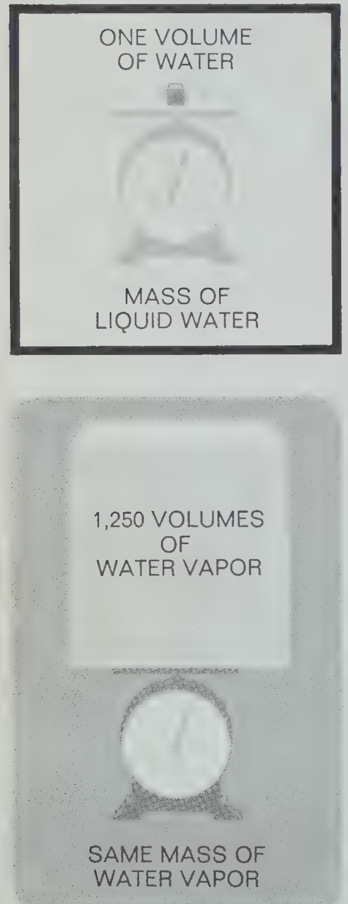


Figure 12-1 The mass of 1 cubic centimeter (cm^3) of water at sea level and at 49°C (39°F) is equal to 1 gram. For example, 18 grams of water occupy a space of 18 cubic centimeters. How much space do 18 grams of water vapor occupy? The answer is 22,400 cubic centimeters—almost 1,250 times the space of the liquid water.

pass through the gaseous atmosphere before it reaches either the water of the oceans or the solid rock and soil of the continents. The solar energy that strikes the outermost part of the atmosphere amounts to about 2 calories per square centimeter per minute (2 $cal/cm^2/min$) on a surface perpendicular to the sun's rays (see note in margin).

12-2 ELECTROMAGNETIC ENERGY

What happens to the incoming energy as it passes through the atmosphere on its way to the earth's surface? To explore this, we need to know something about the kind of energy the earth receives from the sun.

When the sun is on our side of the earth, there is daylight. The light we receive is part of the energy that comes to us from the sun. It is that small part of solar energy to which our eyes are sensitive. The rest of the energy we cannot see, but some of it has an effect on us. The warmth we feel is part of the invisible energy. Another part of it causes our skin to darken when we are exposed to the sun. Other invisible parts behave like radio waves. Still other parts pass right through solid objects, as X rays do (see note in margin).

More than 250 years ago the Englishman Sir Isaac Newton tried to explain the nature of light. He thought light must be made up of tiny particles moving at a very high speed. A little more than a hundred years later, Thomas Young, another Englishman, thought he had proved by experimentation that light was composed of waves of energy. Most scientists of that time believed Young was right and Newton was wrong.

Today we have a theory that light is composed of tiny particles called **photons** and that these move in formation, like marching soldiers.

The reason that Young's wave theory had to be revised is found in the definition of a wave: It is a disturbance moving regularly through a medium. If you toss a stone into a pond, you cause waves to move through the water (the medium). However, the energy from the sun travels many millions of miles through space to reach the earth. Space has no medium. But according to modern theory, there can be no waves without a medium.

Thus, you see why we had to revise the wave theory of light. What appear to be waves are evenly spaced ranks of photons—bundles of energy. We use the "wrong" term for the distance between two photons by calling it the "wavelength" of the energy. This really makes little difference be-

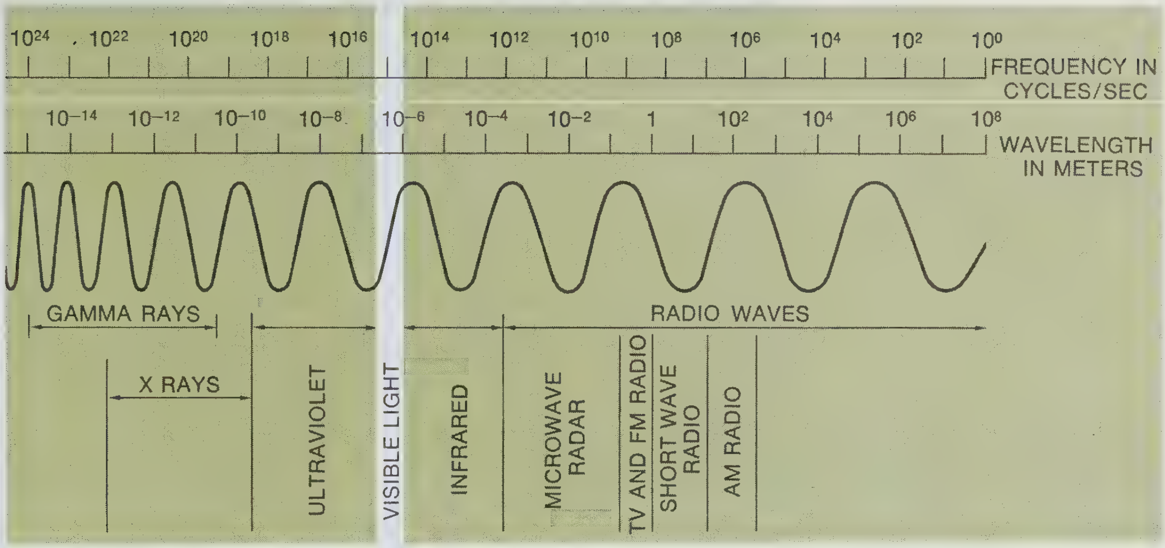


Figure 12-2 In the spectrum, the red colors are light energy having the longest wavelengths our eyes can see. At the opposite end of the spectrum is violet light, the shortest wavelengths we can see. Electromagnetic energy with longer wavelengths than red light is called infrared, and radiant heat and radio waves are even longer wavelengths. Energy having shorter wavelengths than violet is called ultraviolet. Still shorter are the wavelengths of X rays and cosmic rays.

cause we know what we mean when we say "wavelength" in regard to electromagnetic energy.

All of you have seen a rainbow. This display of colors is called a **spectrum** (see Figure 12-2). It is the spectrum, or the range of wavelengths, of visible light.

Scientists must be accurate in their work and in describing things. To be accurate in describing electromagnetic energies, scientists name the energy by its wavelength. All kinds of electromagnetic energy appear to travel at the same speed—300,000 kilometers (186,000 miles) per second. This being true, we then have another way to name these energies. We can talk about their **frequency**, the number of waves passing a point in one second (see note in margin.)

You are familiar with this way of naming radio waves. Each radio station operates at a specific frequency between 500 and 1,600 kilocycles. When you tune your radio, you select one particular frequency to listen to.

Physicists have found that there is a relationship between the intensity of energy and its wavelength. The shorter the wavelength, the greater the intensity. Thus, the very long wavelengths of radio are composed of low-energy photons. The very short wavelengths of cosmic rays consist of high-energy photons.

Figure 12-3 This thermographic photograph of a basketball game shows body heat coming from the players.

Figure 12-4 Reflection and refraction of light rays refer to what happens to the light rays as they strike an object. In the case of refraction, the rays are deflected from a straight path as they pass obliquely from one medium to another.

The detection of the different kinds of electromagnetic energy depends on the wavelength of the photons. Infrared, visible light, and all shorter wavelength energy can be recorded on photographic film (see Figure 12-3). Other wavelengths cannot. The longer wavelengths of electromagnetic energy are detected with instruments that are similar to radio and television sets.

Electromagnetic energy spreads out from its source. It radiates. Because of this, it is called **radiant energy**. What happens when radiant energy strikes matter? This depends on the size of the particles of matter, the composition of the matter, and the wavelength of the energy involved.

Incoming radiant energy may undergo three types of changes: (1) Some or all of the energy may be reflected, as light is reflected by a mirror (see Figure 12-4). (2) Some of the energy may be refracted. For example, water or a piece of glass lets light through but bends its path. (3) The energy may be absorbed, and changed to heat (see Figure 12-5).

Study Guide

1. What is the zenith angle of the sun's rays when the sun is directly overhead?

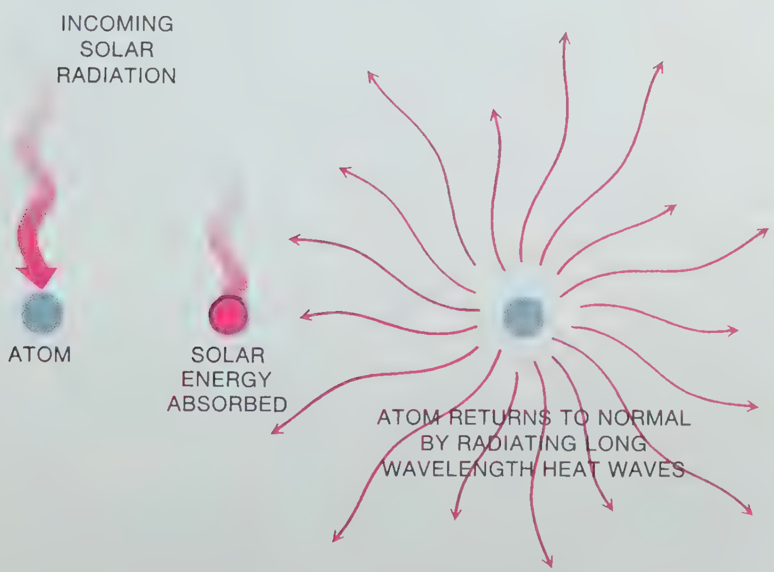
2. What is the basic difference between the matter of the atmosphere and the matter of the lithosphere?
3. Define the solar energy unit called the langley.
4. What is a wavelength?
5. Name two forms of electromagnetic energy that affect your skin.
6. Which radiations have more energy—short wavelengths or long wavelengths?

12-3 SOLAR ENERGY AFFECTS THE ATMOSPHERE

Three things happen to solar radiation on its journey through the atmosphere. First, gas molecules reflect some of the energy back into space. More of this reflection takes place close to the surface of the earth than at the top of the atmosphere.

Second, some of the energy is absorbed by the gases of the atmosphere. When matter absorbs energy, the temperature of the matter increases. This absorbed energy is later released as longwave radiation, which you feel as heat.

Figure 12-5 Matter absorbs short-wavelength energy and radiates this energy as long-wavelength energy, which we feel as heat. Different kinds of matter absorb and radiate energy in varying degrees. For example, transparent glass absorbs little solar energy and remains cool to the touch, whereas a dark mass behind the glass absorbs the energy that passed through the glass.



ion. An atom or group of atoms that are electrically charged by the gain or loss of electrons.

Third, incoming solar radiation converts some molecules of atmospheric gases to ions. The energy also changes the nucleus of some gas atoms and the molecular structure of other gases. For example, at heights of more than 100 kilometers above the earth's surface, only ions of gases exist (see Section 12-6).

12-4 THE TROPOSPHERE

troposphere; Greek: *tropos*, turn + *sphaira*, ball. An area of change.

To bring order to the study of the atmosphere, meteorologists have divided it into layers, each with recognizable characteristics (see Figure 12-6). The region closest to the surface of the earth, where most of the weather occurs, is called the **troposphere**. The troposphere is that part of the atmosphere in which there is constant change. We see and feel changes in it every day.

There is another feature of this lowest portion of the blanket of air around the earth. This is the gradual lowering of the temperature as you go higher into the troposphere. The rate of temperature change with increase in altitude depends on many factors. The rate of change is about 6 Celsius degrees per 1,000 meters (3.3 Fahrenheit degrees per 1,000 feet).

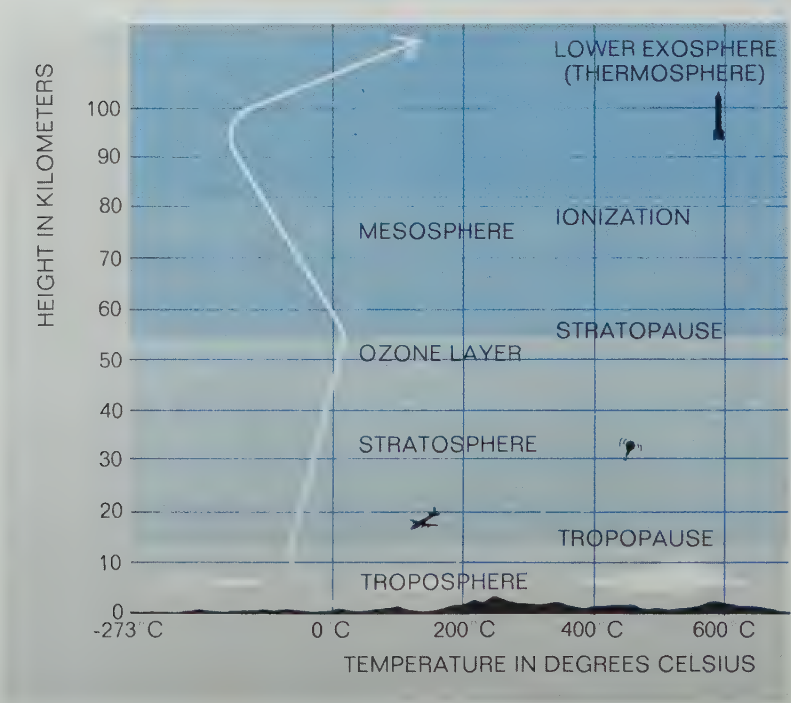


Figure 12-6 Variation of temperature with height in the atmosphere. Explain the sharp changes in the temperature curve.

The upper limit of the troposphere is called the **tropopause** for a very good reason. The temperature at the tropopause averages about −65°C (−85°F). The direction of change in temperature reverses at the tropopause. Above the tropopause the temperature warms with increasing altitude (see Figure 12-6).

12-5 THE STRATOSPHERE

Above the tropopause lies another layer called the **stratosphere**. The stratosphere extends upward to about 60 kilometers (38 miles) above sea level. Its temperature increases from about −65°C to about freezing at the upper limit, the **stratopause**.

In the stratosphere, clouds form so rarely that we may say there are no clouds there. The molecules of water vapor are too far apart to be attracted to one another, and there appear to be no dust particles on which ice crystals can form. At about 50 kilometers above the earth's surface, solar radiation causes some of the oxygen molecules (O_2) to break up into atoms of oxygen (O). These combine with O_2 molecules to form O_3 molecules, a gas called **ozone** (see note in margin).

The presence of this layer of atmosphere so rich in ozone is very fortunate for us. This gas absorbs the shorter-wavelength ultraviolet radiation from the sun and changes it to longer-wavelength energy. Radiant energy in the ultraviolet part of the spectrum is harmful to us. It causes serious skin burns, and too much exposure to it may cause skin cancer.

12-6 ABOVE THE STRATOSPHERE

Above the stratosphere the temperature again drops until at about 80 kilometers (50 miles) above sea level it is approximately −100°C (−150°F). This region between 50 and 80 kilometers above sea level is called the **mesosphere**. In this region, solar radiation changes gas molecules of the atmosphere to ions.

In the mesosphere nitrogen ions are acted upon by cosmic radiation. A neutron drives a proton from the nucleus and an electron from without to produced radiocarbon, C-14, from the nitrogen. (see Section 8-8.)

Above the mesosphere, in the **thermosphere**, the temperature rises rapidly at first and then more slowly to the limits of the atmosphere, where it may be as high as 2,000°C (3,600°F). This high temperature in the thermosphere is the result of the absorption of shortwave solar ultraviolet radiation.

Since the particles in the thermosphere are more widely scattered than those lower in the atmosphere, not many calories of heat are produced by the absorption of solar radiation. When a large piece of matter, such as a satellite or a man doing a space walk, is exposed to solar energy at 400 kilome-

ters above sea level, the amount of energy absorbed may be very high. That is why man-carrying satellites and space suits are designed to reflect most of the energy. This prevents them from absorbing the energy and changing it to heat.

Figure 12-7 These percentages hold true only for the earth. Why do you think these percentages would be different on Venus or Mars?

12-7 THE EARTH'S ENERGY BUDGET

Everything that happens to solar energy during its passage through the atmosphere takes place in less than one thousandth of a second. Only a small portion of the energy that enters the top of the atmosphere reaches the earth's surface unaffected by the matter in the atmosphere. Figure 12-7 illustrates what happens to incoming energy.

About 30 percent of the solar energy is reflected back into space by the atmosphere. Of the remaining 70 percent, 22 percent is scattered by the atmosphere, but in such a manner that it still reaches the earth's surface. Seventeen percent of the solar energy that enters the atmosphere is absorbed by it. This is the energy that produces carbon-14 from nitrogen, converts oxygen to ozone, and ionizes the atmospheric gases. It also adds some heat to the gases.

That leaves only 31 percent of the solar radiation to arrive at the surface of the earth unaffected by its passage through the atmosphere. Notice, however, that 39 percent is scattered or absorbed in such a way that it remains temporarily within the surface-atmosphere system.

Table 12-1 The energy budget of the earth

What happens	*Percentage of total energy*
Reflected and scattered into space	30%
Held in the surface-atmosphere system	70%
Arrives at surface unaffected	31%
Scattered to surface	22%
Absorbed by atmosphere	17%

12-8 ENERGY IS RETURNED TO SPACE

What happens to solar energy that is captured by the earth and its atmosphere? If from year to year energy accumulated in the earth and the atmosphere, the earth would be much

too hot to support life. In fact, the oceans would long since have dried up, and the lower atmosphere, at least, would have become a steamy blanket.

Solar radiation that enters the atmosphere is shortwave radiation. Most of this passes through the atmosphere as visible light. Solar radiation that is absorbed by the atmosphere and the lithosphere is eventually changed to infrared radiation (heat), which is radiated back into space. The infrared radiation emitted by the earth and by the water vapor and carbon dioxide in the air is longwave radiation, which is invisible.

You have learned that the energy of solar radiation is inversely proportional to its wavelength—the shorter the wavelength, the greater the energy. Therefore, when a shortwave radiation is changed to a longwave radiation, such as infrared, energy becomes available to do work. What work can it do? It heats the gases of the atmosphere and evaporates water. In this way, winds are produced and clouds are formed (see Figure 12-8).

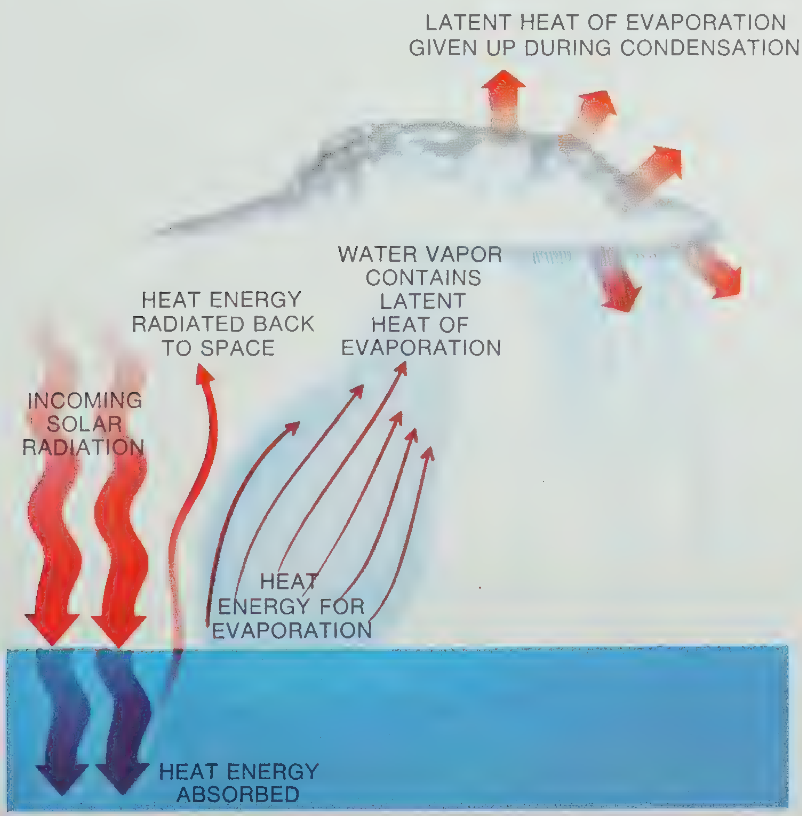


Figure 12-8 Formation of clouds releases heat energy into the atmosphere. In what part of the world would this release of energy be the greatest?

As you can see in Table 12-1, 53 percent of insolation affects the earth's surface. Part of this is received by the land, and part of it by the oceans. Some of this energy causes water to evaporate into the air.

When a certain amount of water vapor accumulates in the atmosphere, clouds form, and it may rain or snow. As water vapor changes to water droplets or ice crystals, it releases heat, which warms the atmosphere. Some of this energy is radiated into space and lost by the earth (see Figure 12-8). Do you remember when and how the water molecules absorbed this heat?

Some of the incoming solar radiation is used by plants to convert water and carbon dioxide to plant tissue. Animals feed on plants. As the plant tissues and animal tissues are oxidized, heat is liberated. Eventually, all the energy is released back to the atmosphere, usually in the form of long-wavelength heat energy.

The rest of the energy enters the soil and rocks on the surface of the earth. Most of this energy is radiated back into space as heat. A small amount of it oxidizes certain minerals. Hence, the earth-atmosphere system absorbs solar energy, transforms it, and radiates almost all of it back into space.

Study Guide

1. What happens to incoming solar radiation received by air molecules?
2. What is it that changes in the troposphere?
3. Is it clear, or cloudy, in the stratosphere?
4. Describe what solar radiation does to molecules in the mesosphere.
5. What percentage of the solar energy that reaches the atmosphere affects the surface of the earth?
6. Incoming solar radiation is chiefly shortwave radiation, and heat is longer-wave radiation. Where does heat come from?

12-9 THE TROPICAL ZONE —AN EXAMPLE OF ENERGY AT WORK

The part of the earth that receives the most solar energy per unit of space is the Tropical Zone. At every place in that zone the sun at some time during the year is directly overhead—a zenith angle of 0 degrees. The Tropical Zone receives about 1.05×10^5 calories per square centimeter per year (105 kilolangleys per year).

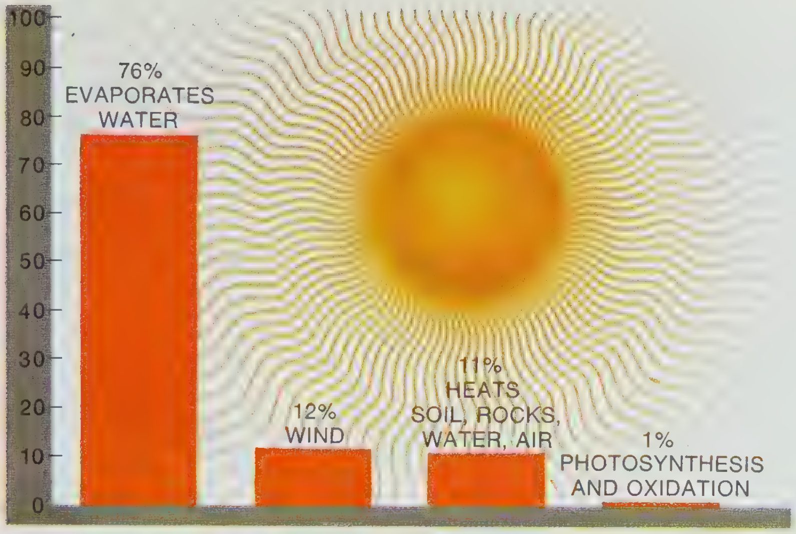


Figure 12-9 The distribution of solar energy in the Tropical Zone

photosynthesis (foh toh SIN thuh sis); Greek: *phos*, light + *syn*, together + *tithenai*, to put. The process performed by green plants that produces carbohydrates.

Of this energy in the Tropical Zone, about 11 percent heats the soil, rocks, water, and air, causing the temperatures that we measure (see Figure 12-9). About 76 percent evaporates water from the oceans and the land. This accounts for 87 percent and leaves us with 13 percent.

The amount of energy used for photosynthesis and not released by plants or animals through oxidation is very little. If we add that little amount to the small amount that oxidizes minerals at the surface of the earth, we may account for about 1 percent. We still have 12 percent to account for.

All of us know that the air moves. We feel it nearly every day as a breeze or a wind. This is what the remaining 12 percent of the energy does—it moves the air. To do so, it is converted to heat at the earth's surface. This heat powers the troposphere—a huge heat engine.

Figure 12-10 Since there is mostly open ocean in the Southern Hemisphere, as shown in this figure, solar energy is used in different percentages. How do the land masses in the Northern Hemisphere account for this difference?

12-10 WORLD USE OF SOLAR ENERGY

If you look at a globe you will notice that much more of the Southern Hemisphere is covered by oceans than by land (see Figure 12-10). In the Northern Hemisphere about 40 percent of the surface is land, whereas south of the equator only 20 percent of the surface is land. This distribution of land and water has an effect on the way solar energy is used in the Northern and Southern Hemispheres. The average receipt of

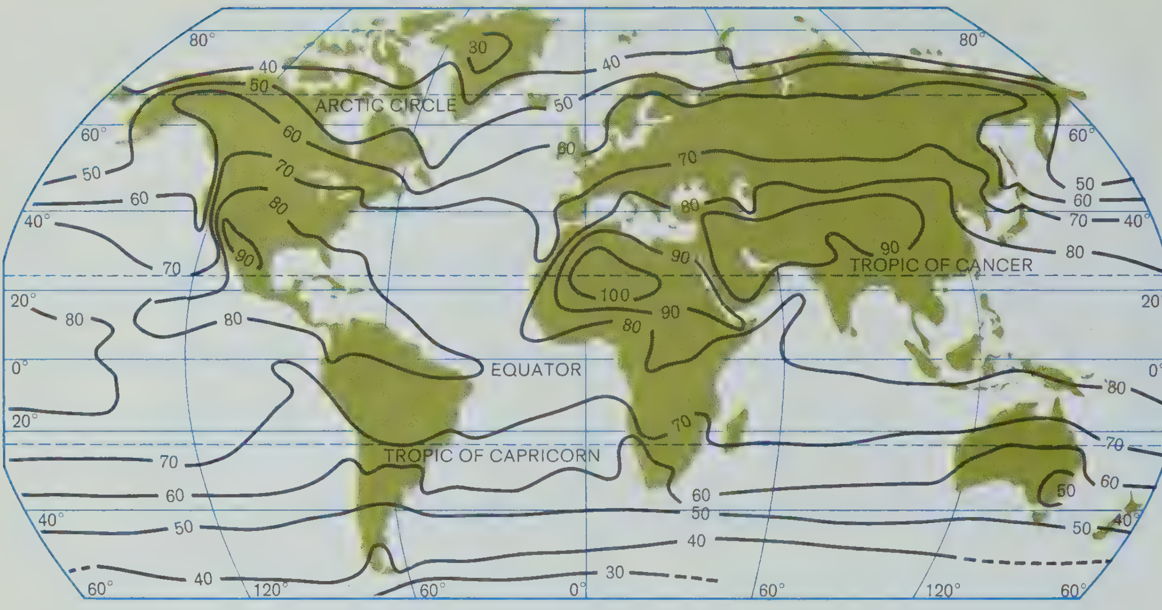


Figure 12-11 Average surface air temperatures for the month of July. You have learned that land changes insolation to heat much more than water does. Therefore, the Northern Hemisphere, where there is more land becomes warmer in summer than the Southern Hemisphere.

energy at the surface for the world as a whole is 72,000 calories per square centimeter per year. Study Table 12-2 for a comparison of the energy budget for the two hemispheres.

More insolation is required to evaporate water in the Southern Hemisphere than in the Northern Hemisphere. In the process of evaporation a large amount of energy is used without changing temperature. Thus, less insolation is converted to heat in the Southern Hemisphere than in the Northern. Note in Figures 12-11 and 12-12 that the temperature change between summer and winter is less in the Southern Hemisphere than in the Northern Hemisphere.

In general, the Southern Hemisphere is cooler than the Northern Hemisphere. You might expect the Northern Hemisphere to get warmer and warmer and the Southern Hemisphere cooler and cooler. However, they do not. The excess

Table 12-2 How incoming energy is used

	Evaporation	*Heating*	*Energy transferred*
Northern Hemisphere	78%	21%	1%
Southern Hemisphere	86%	15%	−1%
Entire earth	82%	18%	0%

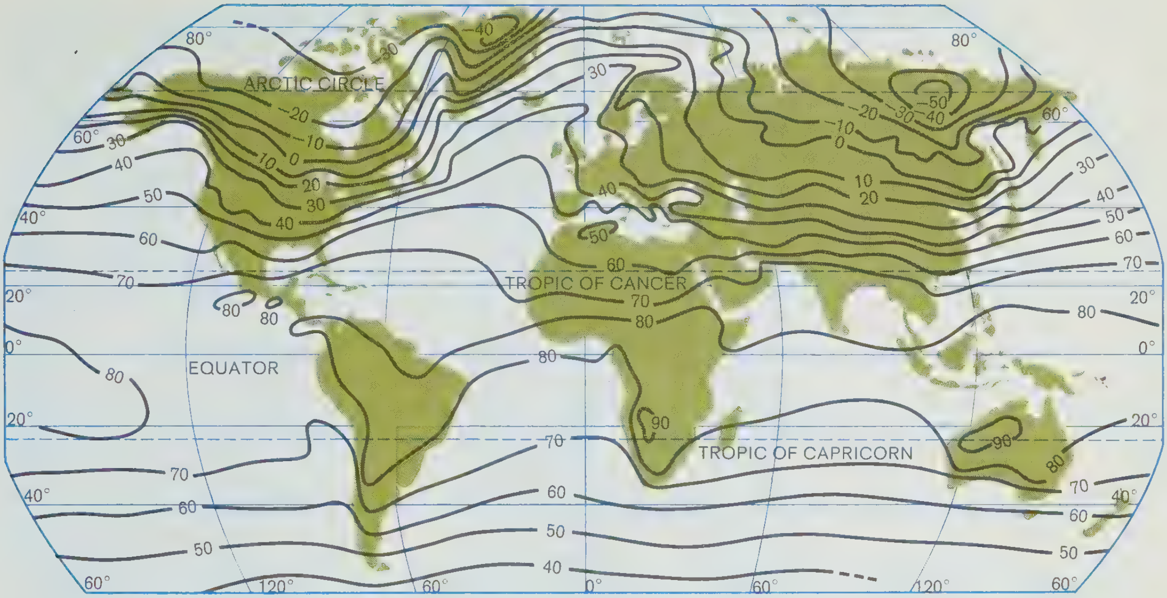


Figure 12-12 Average surface air temperatures for the month of January. Why does the Northern Hemisphere become colder in winter than the Southern Hemisphere?

heat that is generated is spread by winds and ocean currents. In that way, the temperature pattern over the whole world stays about the same from year to year. In later chapters you will see how the oceans help to spread heat. Here, let us examine what happens in the atmosphere.

12-11 THE TROPICAL HEAT BELT

The uneven distribution of incoming solar radiation as it approaches the surface of the earth causes uneven heating of the air, land, and sea. Here we are interested in what happens to the air.

When a gas is heated, its molecules move faster. If the gas is in a closed container with firm walls, heating causes the pressure exerted by the gas to increase. The pressure is exerted in all directions—to the sides, up, and down. If the gas is not in a container, this increased pressure allows the gas to push out in all directions, and the original volume increases.

The air in the tropical heat belt between 10°N latitude and the equator is not in a firm-walled container. Expanding and pushing outward in all directions, the air pushes against the solid earth and sea below it, which do not yield. In pushing against the air to the north and south, the expanding air also meets with resistance from the cooler and therefore denser air that is already there.

The only direction in which this great mass of heated air can readily expand is upward, as shown in Figure 12-13. This it does. It flows upward until the heated tropical air spills to the north and south over the top of the adjacent walls of cooler air. The belt of rising air usually has only weak surface breezes and hence is called the **equatorial calms**, or the doldrums.

What happens next to this tropical air is interesting. If the earth were not rotating on its axis, the rising air would flow directly north and south away from the heat belt. But the earth is spinning on its axis. This spinning affects all movable things. How much they are affected depends on friction. Solids, like ourselves, are held in place by gravity and the friction between our feet and the ground. Fluids—gases and liquids—are also held to the earth by gravity, but there is little static or internal friction in such substances. This lack of friction makes fluids sensitive to the spinning of the earth on its axis.

Study Guide

1. How much energy is received per year by a square centimeter in the Tropical Zone?
2. Describe how most of the energy received from the sun by the Tropical Zone is used.
3. How much energy per year is available to produce wind in the Tropical Zone?
4. Explain how heat moves from equatorial regions to northern and southern regions.
5. Describe what happens to air in the tropical belt.

12-12 A CURIOUS EFFECT OF ROTATION

Suppose you have a wheel that is 36 inches in diameter, as in Figure 12-14. Its circumference is about 113 inches. If the wheel rotates very slowly, one rotation a minute, its **angular velocity** is 360 degrees per minute, since there are 360 degrees in a circle. This is the angular velocity of the rim of the wheel as well as the hub of the wheel. The rim also has a *velocity* of 113 inches per minute.

Now let us consider the rotation of the earth on its axis. The whole earth is spinning eastward at a rate of 15 degrees per hour. How do we know? Since there are 360 degrees in a circle, the earth must turn 360 degrees in 24 hours. Therefore, in 1 hour it must turn 15 degrees, as you learned in Chapter 11. The earth and its atmosphere have an eastward angular velocity of 15 degrees per hour.

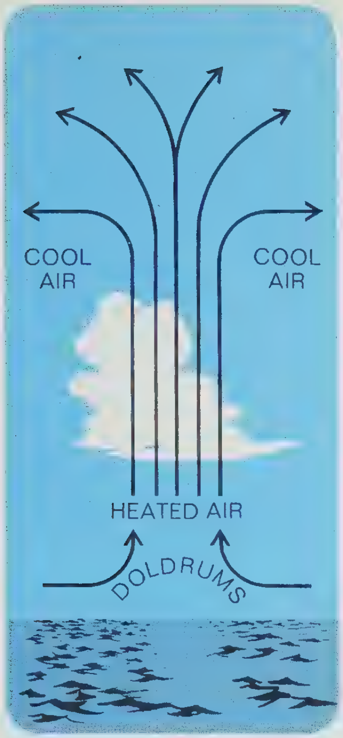


Figure 12-13 In the tropics the pressure of the cooler air masses causes the less dense, heated air to rise. Ancient mariners had difficulty there because there was little wind.

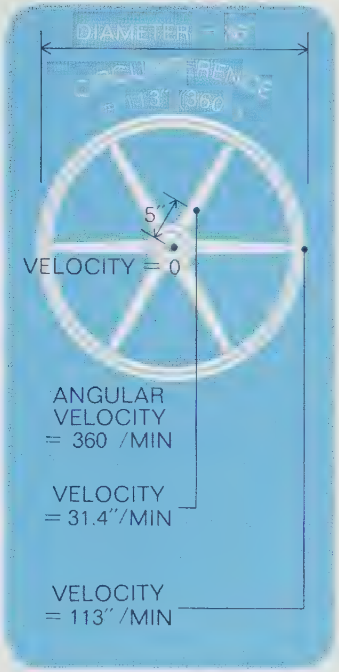


Figure 12-14 What is the velocity of a point of one of the spokes 5 inches from the hub of the wheel? (31.4 inches per minute) What is the velocity of the hub?

There is another way we can describe this eastward motion. The distance around the earth on the equator is about 40,000 kilometers (25,000 miles). If you stand perfectly still at the equator, you and the ground are moving eastward at about 1,660 kilometers (1,040 miles) per hour in relation to a point in space. Standing still in New Orleans (30°N), you are moving eastward at only about 1,440 kilometers (900 miles) per hour. The reason for this is that the distance around the earth at 30 degrees latitude is only about 34,560 kilometers (21,600 miles) instead of the 40,000 kilometers (25,000 miles) it is at the equator.

At each place the angular velocity is the same — 15 degrees per hour. But the "miles-per-hour" velocity changes with latitude from more than 1,600 kilometers (1,000 miles) per hour at the equator to just turning around in 24 hours at the Poles. You can determine your local eastward travel rate in miles

per hour from Table 12-3. All you need to remember is that you are traveling eastward 15 degrees per hour, as you can see in Figure 12-15.

12-13 THE CORIOLIS EFFECT

Now let us get back to the air we left spilling northward and southward from the equatorial heat belt. Let us take the air spilling northward at 10°N latitude. On that parallel, a degree of longitude is 68.128 miles long, so the air, as well as the earth, is moving eastward at 1,022 miles per hour—about the same as at the equator. At 11°N latitude, a degree of longitude is 67.909 miles. That means the eastward travel is only 1,018.5 miles per hour (see Figure 12-16).

Now think of what this means for air that is moving northward and 1,022 miles per hour eastward because of the spin of the earth. As the air moves northward, it moves over the earth's surface that is moving eastward slower than 1,022 miles per hour. The result is that from the surface the air appears to be moving not only northward but also a little

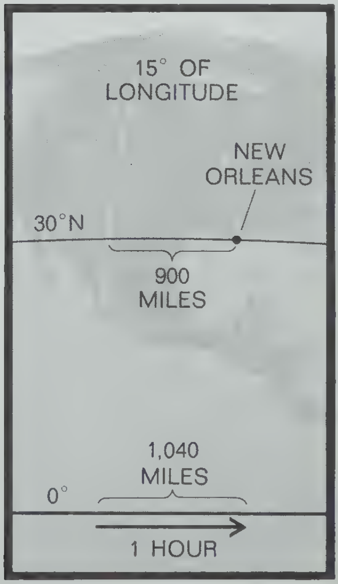


Figure 12-15 Using Table 12-3, construct a graph showing the relation between latitude and velocity.

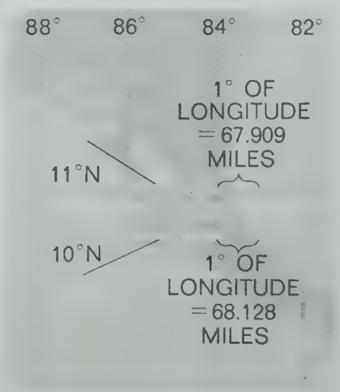


Figure 12-16 Changes in average wind velocity are proportional with the changes in latitude.

Table 12-3 Latitude and eastward velocity

Latitude	*Length of one degree longitude* (*miles*)	*Velocity* (*mph*)
0	69.171	1,040
5	68.911	1,034
10	68.128	1,022
15	66.830	1,002
20	65.026	975
25	62.729	940
30	59.956	900
35	56.726	850
40	53.063	796
45	48.995	735
50	44.552	668
55	39.766	596
60	34.674	522
65	29.315	440
70	23.729	356
75	17.960	270
80	12.051	180
85	6.049	90
90	0.000	0

eastward at a rate of 4 miles per hour (1,022 – 1,018). Look at Figure 12-17 and you will see why this is so.

The first one to explain the details of this phenomenon was a French mathematician, Gaspard de Coriolis (1792 – 1843). This drifting is caused by the spherical shape of the rotating earth. Today it is called the **Coriolis effect**. It operates on any moving fluid, such as the winds of the atmosphere and the currents of the ocean. In the Northern Hemisphere, currents and winds veer to the right, and in the Southern Hemisphere they veer to the left, when you face in the direction of flow.

12-14 THE TROPICAL AIR CELL

We are interested in the result of the Coriolis effect on the movement of the atmosphere. In Figure 12-18 you will see that air rises high in the troposphere from the equatorial heat

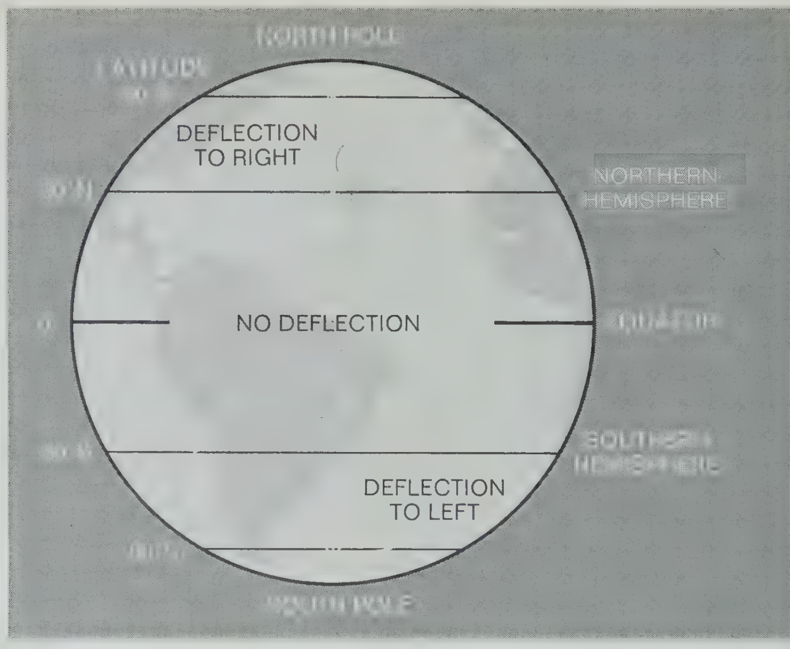
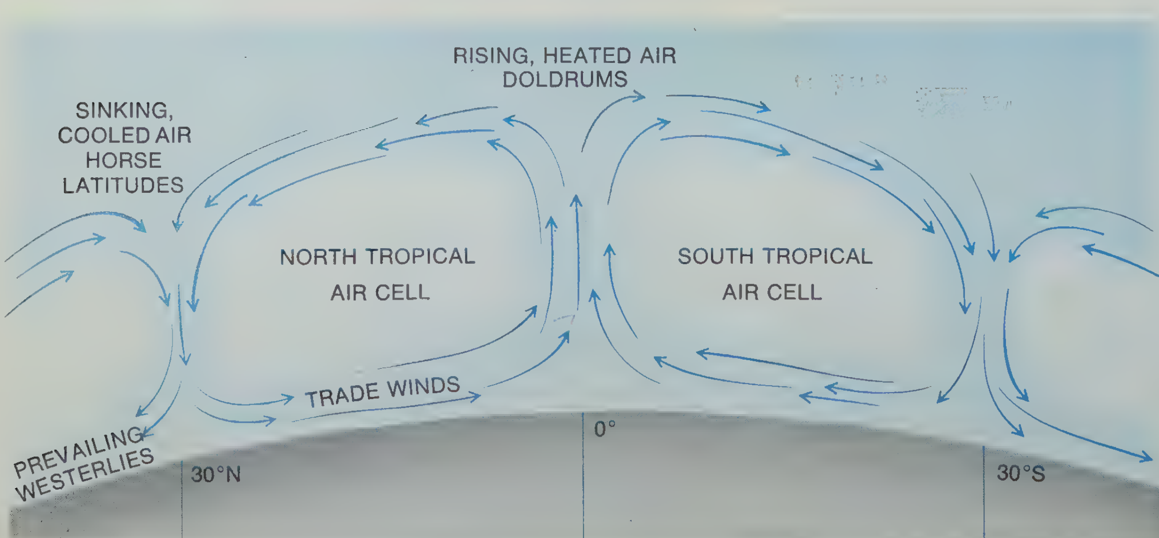


Figure 12-17 A moving object will tend to be deflected either right or left depending on the hemisphere in which the movement occurs. The Coriolis effect also affects projectiles shot into the atomosphere.

Figure 12-18 The heating and cooling of air near the equator cause the circulation of air that we call an air cell. What is the relationship between the tropical air cell and the horse latitudes?



belt. It drifts away from that region in a northeasterly direction north of the equator and in a southeasterly direction south of the equator. Ultimately, this air from the heat belt cools and dries and thus increases in density. When this happens, the heavier air sinks toward the surface of the earth at about 30°N latitude and a little closer to the equator in the Southern Hemisphere. Follow this circulation pattern in Figure 12-18. Such a circulation pattern is called an **air cell.**

Since fluids do not pile up but must spread out, the sinking air must flow away once it reaches the surface. It does this, flowing along the earth in all directions.

The belts around the earth where the air sinks are called the **horse latitudes**. This is a name that dates back to the days of the Spanish exploration of the New World. They are regions with very light and variable winds. Most of the air movement is downward (see note in margin).

The Spanish galleons were often becalmed in these regions, and their horses suffered from lack of water. When the horses died, they were heaved overboard. Thus, these regions became known as the horse latitudes.

When air sinks to the earth's surface, as it does at the horse latitudes, it becomes compressed. This crowds the heat carried by the gas molecules of the air into a smaller space. Thus, the air gets warmer. In Chapter 11 you had an example of adiabatic cooling; here is an example of adiabatic heating. Therefore, the horse latitudes is a zone of sinking, hot, dry air, with only variable gentle winds flowing along the surface of the earth.

The air that pushes northward along the surface from the horse latitudes does the same as the air that flows northward high above the equatorial heat belt. Because of the Coriolis effect, air veers toward the right in the Northern Hemisphere. As a result, the winds north of the horse latitudes blow from the southwest to the northeast. We call these winds the **prevailing westerlies**.

Air that pushes southward from the horse latitudes is also affected by the Coriolis effect. This causes a drift westward. The combined southward and westward movements result in a wind that blows from the northeast to the southwest. This flow of air replaces the air that is swept upward by heating in the zone of the doldrums. These winds from the northeast pushed the sailing vessels engaged in trade with the West Indies from Europe toward the islands. For that reason, they are called the **trade winds**.

Once the air moved by the trade winds enters the doldrums, it expands by heating, rises, and again begins the cycle that starts with air rising in the heat belt. The part of the atmosphere that lies between the doldrums and the horse latitudes is called the **north tropical air cell** (see Figure 12-19).

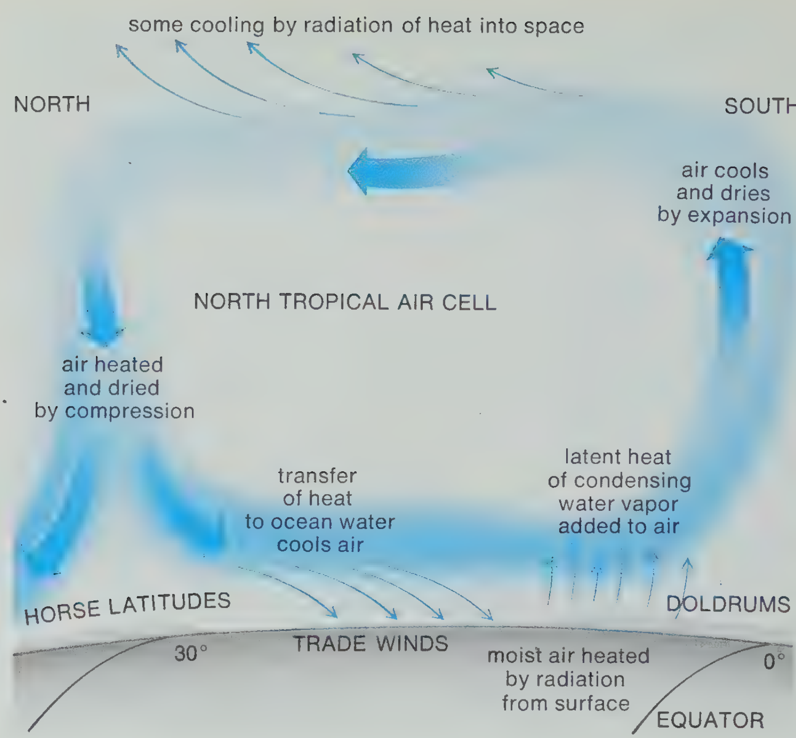


Figure 12-19 The position of this cell shifts a little northward and southward in response to the apparent north and south movement of the sun in the sky. When do you suppose it is farthest north?

Study Guide

1. How do we know the earth is spinning at the rate of 15 degrees per hour?
2. How many miles is an arc of 15 degrees along the equator? along 30°N latitude?
3. Dense air that settles in the horse latitudes starts flowing directly north and directly south. What then happens to this moving air?
4. Because of the spin of the earth, points on the surface of the earth and in its atmosphere move about twice as fast at the equator as they do at 60°N latitude. How does this affect northward moving air?
5. Where in the tropical air cell is air rising and where is it falling?
6. What happens to the temperature of falling air?

SUMMARY

The earth receives from the sun almost all the energy needed for the hydrologic cycle and for atmospheric circulation. Approximately 2 calories per square centimeter per minute are constantly received at the upper surface of the atmosphere on a surface perpendicular to the sun's rays. The equatorial regions of the earth

receive energy in excess of that radiated back into space. This excess energy is moved into the other parts of the earth by winds and ocean currents. Since the Northern Hemisphere contains more land surface, more of the solar radiation is converted to heat there than in the Southern Hemisphere. Solar energy converted to heat provides the energy for planetary circulation.

REVIEW QUESTIONS

1. The outside of a space vehicle standing on its rocket in the sunshine at Cape Kennedy gets hot. Will it be hotter, or colder, while orbiting between 150 and 200 miles above the earth's surface? Explain your answer.
2. The heat equator is an imaginary line around the earth designating its hottest zone. This lies several degrees north of the equator. Explain why this is so.
3. The text states that fluids respond to the Coriolis effect but we do not. Describe the conditions under which we are affected by the Coriolis effect.
4. Normally, a region heats up during daylight hours and noticeably cools during the night. Explain why it does not cool very much on a night when there is a heavy cloud cover.
5. Arabian tribesmen in the deserts of Asia Minor wear a burnoose. This is a long gown of white woolen cloth. Explain why they wear such heavy clothing in a hot desert country.
6. Where would you expect to find the most noticeable Coriolis effect on moving air—over the land, or over the sea? Explain why.
7. What allowance must be made for the Coriolis effect when a projectile is shot into the atmosphere in the Northern Hemisphere?
8. Why does the amount of energy received from the sun at any one place on earth vary from day to day?
9. Of what value to us is a layer of atmosphere rich in ozone?
10. In what ways is the energy captured by the lithosphere returned to space?
11. What causes the high atmospheric pressure in the horse latitudes?
12. How is the amount of energy received by different parts of the earth balanced over the entire earth?

CHAPTER 13

THE GLOBAL WIND BELTS AND AIR MASSES

In the previous chapter you learned two facts that are important to remember throughout this chapter. The first fact was that only the Tropical Zone receives more solar energy in a year than it radiates back into space. All other parts of the earth receive less solar energy in a year than they radiate into space. The second fact was that the tropical air cells spill air into the middle latitudes north and south of the Tropical Zone, as shown in Figure 12-19. In this chapter you will explore what happens in the troposphere over the North Temperate Zone and the North Polar Zone.

13-1 THE PREVAILING WESTERLIES

In review, rising air in the doldrums carries with it a considerable amount of energy. Matter on the earth's surface and in the atmosphere converts solar radiation to heat energy. In turn, heat energy causes air to expand and rise. As this heated air flows across the top of the north tropical air cell, some of its heat is radiated into space. However, much of this heat is retained by the air. When the tropical air sinks in the horse latitudes, it is compressed, and the energy it contains is crowded into a smaller space. This compression raises the temperature of the air. Remember, this process is called adiabatic heating.

At the earth's surface in the horse latitudes, some of the sinking air is diverted toward the southwest and reenters the north tropical air cell. The rest flows northeastward, into the region of the North Temperate Zone. The air flowing away from the horse latitudes is warm and dry. Therefore, it can absorb and hold more moisture than it contains when it arrives at the surface.

The green rain shadow on the Sierra Nevadas in California, with the brown Mojave Desert in the background

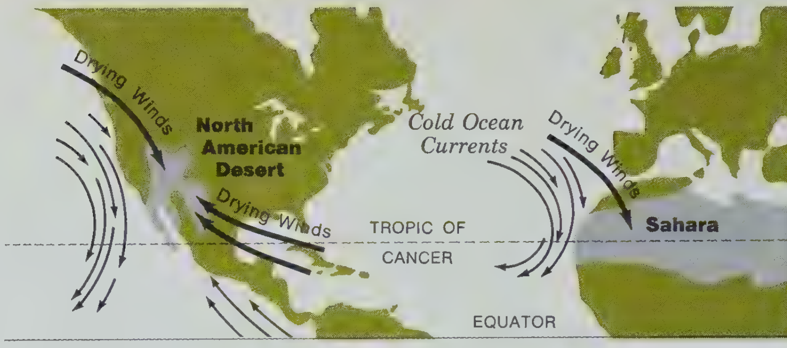


Figure 13-1 The major deserts of the world appear in the areas of the horse latitudes.

Over the oceans, the air soon becomes laden with moisture. Over the land, where there is little water, the warm, dry air absorbs whatever moisture is available. In this way, deserts are formed. Notice in Figure 13-1 that the Sonoran Desert, in North America, and the Sahara, in Africa, coincide with the belt of the horse latitudes.

The air flowing northward from the horse latitudes soon passes over the part of the earth's surface where the meridians begin to converge noticeably. The Coriolis effect gives an increasingly eastward twist to this northbound stream of air. As a result, the air across the North Temperate Zone flows toward the northeast. Interestingly, this situation also causes the velocity of the air to increase (see note in margin). In the days of sailing ships, the journey from America to Europe was made with the aid of these winds. In similar latitudes in the Southern Hemisphere, the winds from the west are very steady and strong. Sailors called the region south of 40°S latitude "the roaring forties."

The Coriolis effect increases toward the poles. The air will be moving 5.4 miles per hour faster at 41°N than at 40°N.

In both hemispheres these winds are called the **prevailing westerlies**. They carry warm air poleward and distribute heat that reaches the earth as solar radiation in the Tropical Zone. The prevailing westerlies start their poleward journey as dry air and pick up moisture as they travel. They move toward the poles until they meet air from another great air cell, the **polar air cell**.

13-2 THE POLAR AIR CELL

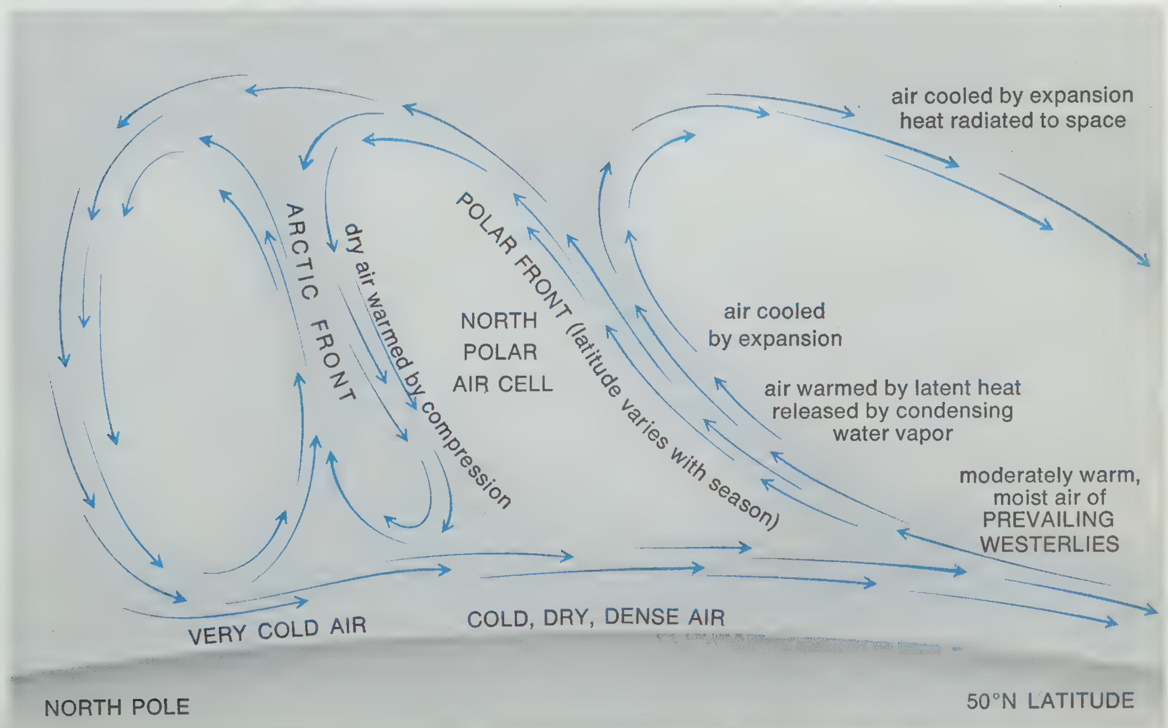
The Polar Zones are cold. Therefore, the air over them is also cold. Cold air is denser than warm air for two reasons: (1) It has more molecules of oxygen and nitrogen per unit of volume. (2) It contains less water vapor.

For these reasons polar air is cold, dry, and dense. This means that a column of polar air is heavier than a column of warm air of the same volume. Thus, atmospheric pressure in the North Polar Zone tends to be greater than the pressure in the North Temperate Zone. This higher pressure forces the polar air to move southward over the earth. Because of its greater density, the polar air slips under warmer, less dense air that is moving northward.

During summer the southern margin of the cold air is in the vicinity of 50°N latitude across most of North America and the North Atlantic and Pacific oceans (look ahead to Figure 13-4). The air that moves north from the horse latitudes slides up the sloping front of the polar air mass. This rising air divides near the tropopause. Some of it flows southward, completing a circulating air cell between the horse latitudes and the polar air mass. The other part of this rising air moves northward and sinks in the North Polar Zone to complete the polar air cell. This is shown in Figure 13-2.

As more and more air is added to the polar air cell, the atmospheric pressure increases at its base. Such cold air, there-

Figure 13-2 Polar-air-cell circulation depends on the northward movement of the relatively warm, moist air in the prevailing westerlies. The latitude at which the cell is located changes with the seasons. Why?



fore, has the power to press southward and flow into the region of the prevailing westerlies. Such action, called a **polar outbreak**, makes more room for the air descending in the North Polar Zone.

13-3 THE ENERGY BALANCE IN THE POLAR ZONES

In Section 12-10 you saw that the Tropical Zone receives an amount of solar energy in excess of the amount it radiates back into space. The opposite is true of the Polar Zones. Although the Arctic Circle lies at $66\frac{1}{2}°$N latitude, we will consider the true North Polar Zone to be the region between 70°N latitude and the North Pole.

Because the sun's rays strike the Polar Zones during only part of the year, and then only at a high zenith angle, there is little incoming energy per unit of area. The solar energy received in the North Polar Zone probably never exceeds 1 kilolangley per year. So thus far, we have a gain of 1 kilolangley. Evaporation from the land, from ice fields, and from the open sea uses about 8 kilolangleys per year, so the North Polar Zone is "in debt" about 7 kilolangleys per year. No part of the earth loses more energy than it gains. Therefore, 7 kilolangleys per year must be transferred from the Tropical Zone, across the North Temperature Zone, into the North Polar Zone. Some of it is transferred by winds, but most of it is transferred by ocean currents. In the South Polar Zone the heat debt is even greater—probably about 11 kilolangleys per year.

Study Guide

1. Which geographic zone receives an excess of solar energy?
2. Explain why the temperature of descending air rises.
3. Why are there deserts in the region of the horse latitudes?
4. Why do the prevailing westerlies actually move from southwest to northeast?
5. Why does air pressure at the surface tend to be higher in the Polar Zones than in the Temperate Zones?
6. Why is heat constantly transferred to the Polar Zones?

13-4 NAMES AND SYMBOLS FOR THE AIR MASSES

Scientists use a great many symbols to represent ideas or terms they use frequently. Meteorologists use symbols for the air masses. As you have learned, there are two principal kinds of air masses, based on the amount of heat energy of

the air: the cold, polar air masses and the warm, tropical air masses. The symbols used for these are *P* for polar and *T* for tropical.

Air masses form over either the ocean or the land. Ocean air masses are represented by the symbol *m*, which stands for maritime (oceanic). Air masses that form over the land are represented by the symbol *c*, which stands for continental. The two sets of symbols are combined to designate a particular air mass. A continental polar air mass is written *cP*, and a maritime tropical air mass is written *mT*.

13-5 THE AIR MASSES OF NORTH AMERICA

The United States and southern Canada are wedged between the regions where a warm, tropical air mass and a cold, polar air mass form. It is across these parts of North America that the winds move excess heat from the tropics to the Arctic.

Often, during the summer, the tropical air mass pushes northward and invades the northern United States and southern Canada. In the winter the polar air mass often pushes southward across southern Canada and invades the United States. In addition to being between these great air masses, North America lies between two great bodies of water, the Pacific Ocean and the Atlantic Ocean.

Both the tropical and the polar air masses extend over land and water. Does this have any effect on the air in those masses? Which portions of each of these air masses will contain more moisture—the portions over the continents or those over the oceans? What is the effect of the moisture content of the air on the energy needed to warm it and on the energy given off as it cools? The answers to these questions are important to an understanding of the way in which incoming solar radiation is used and to an understanding of the hydrologic cycle.

Because there is a marked difference between the air over continents and the air over oceans, the great air cells, tropical and polar, are divided into sections. To the south of us, the north tropical air cell lies over the Pacific Ocean, north-central South America, the Caribbean Sea, and the Gulf of Mexico. Figure 13-3 shows the portions of the north tropical air cell nearest us. Why does a continental tropical air mass form only in summer? What is the connection between this air mass and the semiarid-to-desert condition of our Southwest and of northern Mexico? What will hot, dry air do to the moisture content of the soil across which it sweeps?

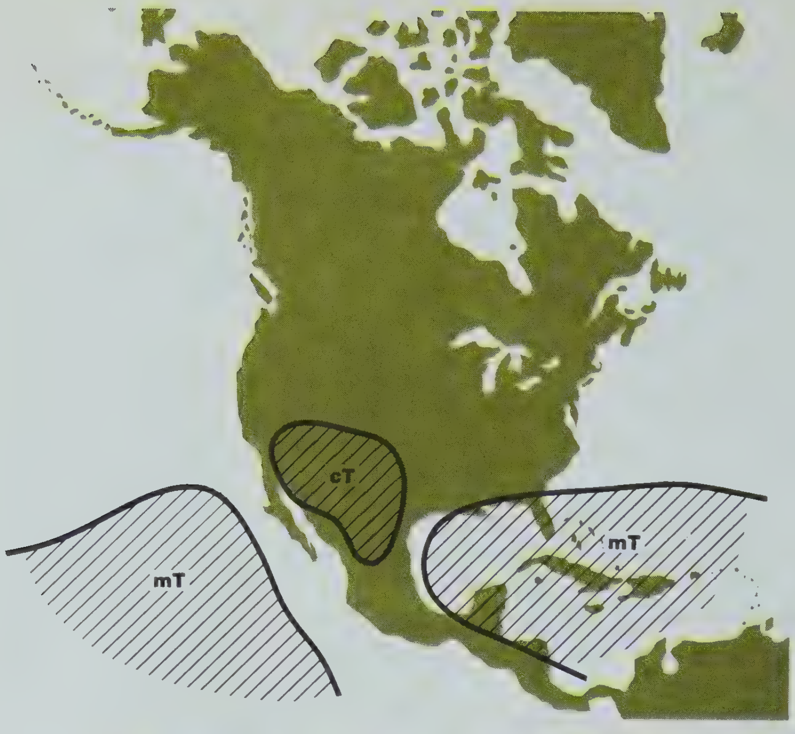


Figure 13-3 The north tropical air cell and the portions of North America that are affected by its movement

Figure 13-4 The major polar air masses that affect North America

Now look at Figure 13-4, which is a map of the polar air masses. Notice that the two maritime air masses are labeled *cool*, and the continental air mass is labeled *cold*. Notice that *cool* and *moist* are linked and that *cold* and *dry* are linked. Here is a clue to why they are associated: The heat held in water vapor can be transferred to air molecules. When water vapor condenses to form clouds or fog, what happens to the original latent heat of vaporization? The specific heat of air is 0.24, whereas that of water is 1.0. Would the condensation of a little water vapor in the air supply enough heat to warm the air appreciably? Let us find out.

At the freezing point, 1 cubic meter of air can hold only 4.85 grams of water vapor. The latent heat of vaporization of water at 0°C is 595 calories per gram. A cubic meter of air at sea level at 0°C weighs about 1,300 grams. Since the specific heat of air is 0.24, it will take 312 calories to raise this cubic meter of air 1C°.

$$1{,}300 \text{ grams} \times 0.24 = 312 \text{ calories}$$

How many calories will be given up by condensing 4.85 grams of water vapor to water at 0°C? (Hint:The amount of energy necessary to vaporize 4.85 grams of water to water vapor will be the same amount given up when that amount of water vapor is condensed back to water.)

$$4.85 \text{ grams} \times 595 \text{ calories} = 2{,}886 \text{ calories}$$

Enough heat (2,886 calories) would be released by condensing 4.85 grams of water vapor (a very small amount) to raise the temperature of a cubic meter of air a little more than 9C°.

$$2{,}886 \text{ cal}/312 \text{ cal/m}^3/\text{C}° = 9\text{C}°/\text{m}^3$$

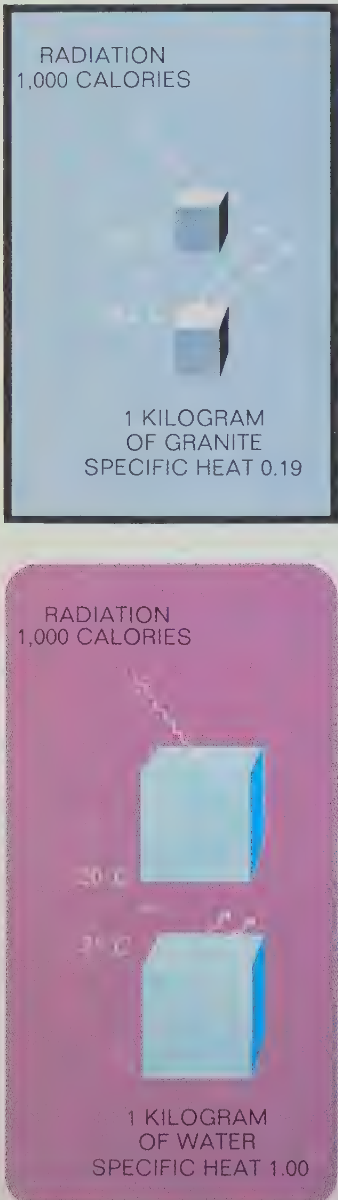
Such total condensation of the water vapor in the air never occurs, but condensation of just 1 gram of water vapor per cubic meter of air will raise the temperature 2C°.

What does this tell us about our problem? It means that over the oceans a great amount of incoming solar radiation evaporates ocean water and converts it to water vapor. In this process, the oceans are not greatly warmed by solar radiation. The air in contact with this cool water loses heat and thus remains cool. It is only when the water vapor is condensed to fog, clouds, rain, or snow that its heat is released to warm the air.

Over the land the situation is different because of the low specific heat of soil and rocks. Heating of a relatively thin layer of soil and rocks by solar radiation produces a large

Figure 13-6 This polar air mass is advancing over the land from the northwest. The unstable air from the southeast is being displaced by cooler air. The cloud formation indicates the leading edge of the cold front.

Figure 13-5 Solar radiation heats up a sand beach much more than it heats up the water next to it. The difference in the effect of insolation is due to the difference in the specific heat of sand and water.



difference in the temperatures of the surface materials and the air above them. Figure 13-5 illustrates this difference. As a result, heat flows into the air over land. The air masses over oceans are therefore cooler than those over land in summer. Why would the reverse be true in winter?

13-6 WHAT HAPPENS BETWEEN THE AIR MASSES?

Most of the United States becomes a battleground between the polar air masses to the north and the tropical air masses to the south. In the summer the tropical air masses dominate and push northward, carrying with them heat and moisture. Wherever the tropical air masses press against the southern edge of the polar air masses, storms are created (see Figure 13-6). Meteorologists have a name for the border between two different air masses. They call this border a **front** (see Section 15-1).

In the winter the polar air masses are usually the more powerful, and they press the front far to the south in the United States. As air masses surge back and forth across the United States, they bring warm or cold air with them. At the front, there usually are storms, whereas some distance behind them, in the body of the air mass, the weather is fair. We shall take a closer look at storms, but first let us examine air over land and water.

13-7 THE EFFECTS OF CONTINENTS AND OCEANS

The great wind belts received their names from sailors. Those of us who live on continents seldom notice these general winds, nor do we recognize them as easily as sailors do at sea.

There are two good reasons for this. First, the surface of the continents is rough as compared with the surface of the oceans. This roughness interferes with the uniform flow and direction of winds blowing across the surface. Only in vast regions of nearly smooth land, such as the broad basin of the Mississippi River, are the prevailing westerlies usually noticed.

The general winds you have been reading about are layers of air moving along the surface of the earth. They can extend upward from the surface to about 5 kilometers. The great mountain systems of our continent rise high enough to interfere with the flow of these winds. For example, the main crest of the Sierras in California reaches 3 kilometers (10,000 feet), and the Continental Divide in Colorado is even higher—almost 3.7 kilometers (12,200 feet). These north-south mountain ranges act as barriers to the uniform flow of the surface winds. Therefore, the northeastward direction of the air does not prevail at the surface. Figure 13-7 outlines these mountain barriers. Which side of the mountains in the photograph at the beginning of the chapter has more rainfall? Why?

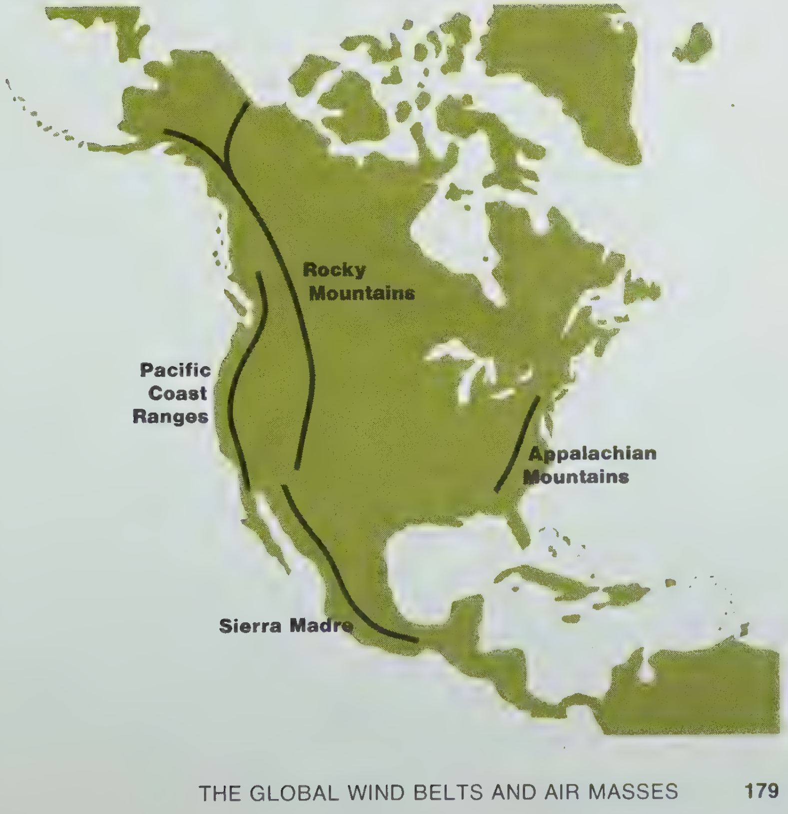


Figure 13-7 Prevailing westerlies are not usually noticeable in most parts of North America because of the chains of mountain barriers.

The varied surface of the continents—partly rocky or sandy, partly covered with grasses and partly with forests—makes the heating and cooling very uneven. This is the second reason the direction and velocity of the winds that flow across the continents are greatly altered. These ideas are developed more fully in the next chapter.

The high specific heat of water causes it to heat and cool slowly. The low specific heat of rock and soil causes them to heat and cool rapidly. Remember that 1 calorie will increase the temperature of 1 cubic centimeter of water 1C°. The same amount of heat will increase the temperature of 1 cubic centimeter of rock about 1.7C° (3F°). That amount of rock weighs two and a half times as much as the water. As a result, the continents heat and cool much more irregularly and quickly than the oceans.

There is another reason why the oceans do not heat up as much as the land does. Oceans have depth, and radiant energy penetrates below the surface. Also, ocean water is stirred up by the wind. These combine to heat the oceans to greater depths than occurs on the land. Because the ocean has a greater heat capacity than the land, it experiences much smaller temperature changes.

Study Guide

1. Explain why the Temperate Zones have the most variable weather.
2. Why does the temperature of the air vary more rapidly than the temperature of the oceans?
3. Why are summer air masses over the oceans cooler than adjacent ones over the land?
4. Explain why the major wind belts are more easily observed over the oceans than over the continents.

13-8 A NEW ENGLAND NORTHEASTER

Now we can describe what happens when a tropical air mass and a polar air mass collide. We shall examine the situation over the North Atlantic Ocean, where the irregularities of the continent do not interfere with the general winds.

During the winter the maritime polar (*mP*) air mass spreads southward to lie between 40° and 37°N latitude. At the same time, the northern front of the maritime tropical (*mT*) air mass is between 15° and 20°N latitude. There is a broad region of mixed air between these air masses. As the days become longer in the spring, the front of the maritime tropical

Figure 13-8 The air masses that are present during a northeaster are shown here. The direction of the wind is not shown. From which directions would winds be blowing? Why?

air mass moves northward (see Figure 13-8). Because the North Polar Zone, still largely in darkness, has not yet warmed, the southern front of the maritime polar air mass remains stationary.

The maritime polar air mass is cool and moist. The maritime tropical air is warm and moist. Of the two, the cool northern mass is denser and contains less water vapor. At its southern edge it is a thin layer lying on the cool ocean water. Its upper surface slopes upward toward the north, as shown in Figure 13-9.

The northward-advancing front of the warm, tropical air slides up the sloping cool front. Such a condition produces a temperature inversion. Because of radiation from the earth's surface, a column of air is normally warm at the bottom and cool at the top. In a **temperature inversion**, cold air is at the bottom and is topped by a layer of warmer air.

The warm, tropical air expands as it rises and moves northward along the slope of the cold, polar air mass. The expan-

Figure 13-9 The warm air moving from the south will glide over the denser, cold air moving from the north. A front is often characterized by rain. Notice the temperature inversion.

sion of the rising air causes its temperature to decrease. This is an example of adiabatic cooling. The decrease in temperature results in condensation and the formation of clouds. This, of course, causes large amounts of latent heat energy to be released into the air (see Figure 13-9).

The increase in the energy content of the air causes the forming storm to become intense. Heavy rain and high winds blow on shore from the northeast. The land is still cold from winter. Heat is transferred from the air to the land. Thus, the temperature of the humid air is decreased, increasing the rainfall. Low clouds and fog often accompany the rain.

While New England experiences one of these late winter storms, the weather is miserable for a few days. Soon most of the excess energy is drained out of the tropical air mass. It begins to weaken and retreats southward. Clear, cool weather results along the coastal areas. Although northeasters are most common in late winter and early spring, they may occur at any time of year.

13-9 A TEXAS NORTHER

Now let us see what happens when air masses collide over the continent. In the broad and relatively smooth Mississippi basin, the opposing air giants are the continental polar (*cP*) air mass—cold, dry, and very dense—and the maritime tropical (*mT*) air mass—warm, moist, and less dense.

You can recognize where the southern edge of this air mass lies if you observe how far south snow remains on the ground for many days.

As the North Polar Zone goes into its long winter's night, the *cP* air mass increases in density and pushes southward. The *mT* air mass is the warmest and wettest of the air masses that invade the United States. In the winter it lies over the Gulf States as a warm, humid blanket. Because the winter

sun is low, the land is often colder than the air mass. This results in a temperature inversion, which at its northern boundary lies as high as about 1 mile above sea level. Figure 13-10 shows where these air masses meet.

As winter progresses, the cold *cP* air slides south under the *mT* air mass. Then things begin to happen! The moisture of the warm air condenses and falls as snow. The heat energy that is released from this condensation of water vapor causes strong updrafts of air.

These updrafts, in turn, cause cold, dense air from the north to flow southward. The inflow of rapidly moving cold air drops the surface temperatures to well below 0°C and often below −20°C. The wind sweeps snow before it, and a blizzard roars southward across the panhandle of Texas. A Texas norther is in action.

When the pressure of the *cP* air mass has pushed the *mT* air mass far to the south, cold, clear weather follows. Slowly the tropical air mass regains power, and as the polar air retreats, the warm air slips northward over the land to replace it.

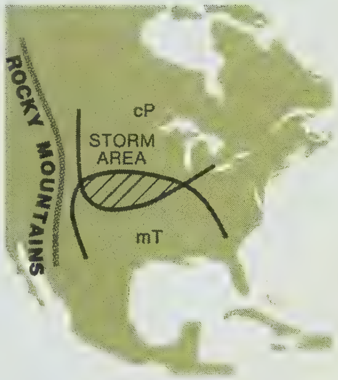


Figure 13-10 When the cold, continental polar air mass pressures its way south and pushes into the warm air of the maritime tropical air mass, a Texas norther usually develops.

13-10 ANOTHER AIR MASS

Let us look at the effects of one more air mass on the United States. West and southwest of California, over the Pacific Ocean, there lies a warm, moist *mT* air mass. Only in winter does wind from this air mass blow onto the land in southern California. This air mass (see Figure 13-11) is somewhat cooler and drier than either of the tropical air masses from the Atlantic Ocean that invade the continent. The winter invasion of southern California by maritime tropical air produces mild winters with some rain.

The mountain barrier that rises not many miles east of the coast drains this air mass of much of its moisture. As the surface air is forced to climb the west side of the mountains, it expands and is cooled. This cooling produces snow in the higher parts of the range.

As the air continues to flow northeastward, it descends the eastern flanks of the mountains, compresses, and becomes warmer and drier. (This is an example of adiabatic warming.) This warm, dry air helps to create the desert areas of the Southwest. It licks up what moisture is available and drops it on the west side of the Rockies as it climbs that towering range.

A Mediterranean weather pattern is one with mild winters accompanied by some rain. The summers are dry. It gets its

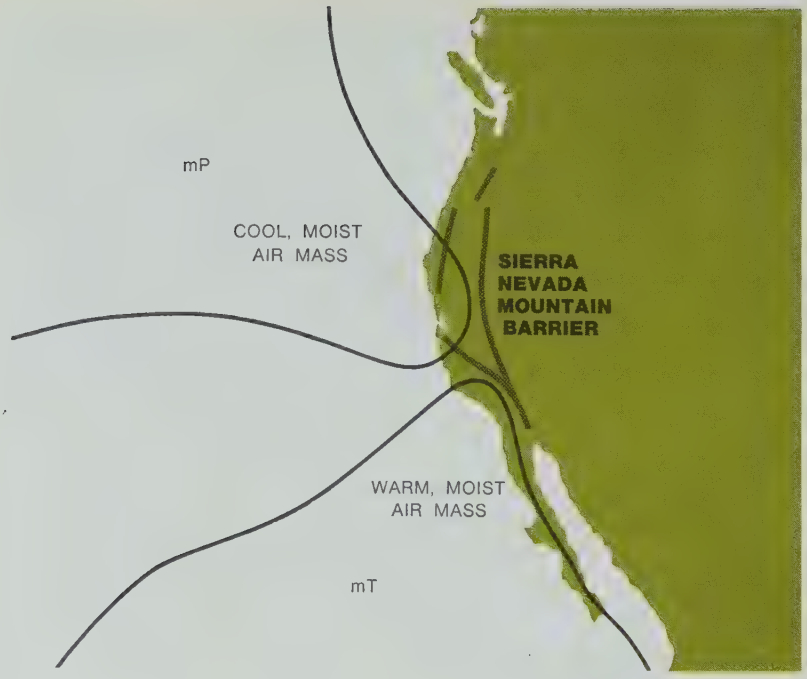


Figure 13-11 When maritime polar and maritime tropical air masses meet off the coast, the region experiences a mild, wet winter. The West Coast of the United States has this type of Mediterranean climate during its winter.

name from the fact that northwestern Africa and southwestern Europe, at the western end of the Mediterranean Sea, have this weather pattern. It is similar to the pattern of weather in southern California.

Study Guide

1. What causes a front?
2. Why are fog and drizzle common in early spring on the New England coast?
3. What causes a temperature inversion?
4. Why do blizzard conditions often accompany a "Texas norther"?
5. Explain why most of the annual precipitation in southern California occurs during the winter months.

SUMMARY

The great wind belts of the earth are powered by the solar radiation received by land and ocean. These belts are most clearly defined over the oceans. Proceeding northward from the equatorial regions, at the surface of the earth, are the doldrums, a region of rising, heated air; the trade winds, which blow from the northeast; the horse latitudes, a region of cool, descending air; the prevailing westerlies, which blow from the southwest; an ill-defined belt of

rising air; the polar winds from the northeast; and in the Arctic, a region of sinking, cold, dry air.

The warm air moving away from the Tropical Zone produces air masses that have different characteristics over the ocean than they have over the land. Similarly, air masses moving toward the equator from the Polar Zones have different characteristics over the land than they have over the ocean. The global winds of the great wind belts play a major part in determining the general weather of a region. Contact between tropical and polar air masses may produce a line of storms along the fronts, as in the case of the northeaster and the Texas norther.

REVIEW AND DISCUSSION QUESTIONS

1. The peninsulas of Lower California and of Florida are at about the same latitude. Why is Baja California mostly desert, whereas Florida is well watered?
2. Why do the central parts of the United States and southern Canada have more extreme temperatures during a year than their sea coasts?
3. The coastal regions of northern California and Oregon are covered with luxurious forests. The eastern portions of northern California and Oregon are semiarid and even desert in some places. Explain why this difference occurs in a relatively short distance.
4. Explain how the Coriolis effect increases wind velocities as the latitude increases.
5. If the Arctic Ocean were not covered with ice, what changes would you expect in the air of the north polar air cell?
6. The *mT* air mass that moves out of the Gulf of Mexico is about 6,000 feet thick. This air mass moves up the Mississippi Valley. Why would you not expect this air mass to affect directly the region west of the Rocky Mountains? Might this air mass directly affect eastern Pennsylvania?
7. The difference in temperature between the warmest and coldest months in San Francisco is much less than that in St. Louis. Both cities are at about the same latitude, and their elevations above sea level are not very different. How do you explain the temperature difference?
8. Why is the air temperature usually cooler the higher you climb up a mountain?
9. Why do high-flying aircraft sometimes leave a white trail behind them?
10. Describe the atmospheric conditions of Mediterranean weather.
11. What are the differences between a northeaster and a Texas norther?

CHAPTER **14**

AIR PRESSURE AND WINDS

In the previous chapter you learned that air descends in the horse latitudes and in certain latitudes of the Polar Zones. When the air meets the earth's surface, it spreads northward and southward. This surface flow is caused by a difference in pressure. Air flows from a region of higher pressure to one of lower pressure. Meteorologists use the terms **high** and **low** for areas of relatively higher and lower atmospheric pressure. In this chapter we shall investigate highs and lows.

14-1 THE MEASUREMENT OF AIR PRESSURE

In the seventeenth century an Italian physicist invented an instrument that enabled him to accurately measure the pressure exerted by a column of air. Evangelista Torricelli was educated in Rome as a mathematician and wrote a book about the branch of physics called mechanics. Galileo read this book with interest. As a result, Galileo invited Torricelli to Florence to work with him.

Galileo suggested to Torricelli that he investigate why a lift pump can lift water no more than 33 feet. To Galileo, this was contrary to Aristotle's statement, "Nature abhors a vacuum." If Aristotle was correct, there should be no limit to the height water can be raised by a lift pump.

Torricelli had performed many experiments having to do with the flow of fluids. It occurred to him that the behavior of the pump might have something to do with that subject. He had the idea that air pressing down on the surface of water pushed the water up into the tube beneath a pump.

To test this idea, Torricelli used a fluid that is much denser than water. He used mercury, which has a density of 13.6 grams per cubic centimeter. He sealed a long glass tube at one end and filled it with mercury. Then he placed the open end of the tube into a bowl of mercury, as shown in Figure

The eye of a hurricane is an area of quiet low pressure surrounded by raging winds and waterfall rain.

Figure 14-1 Evangelista Torricelli (Italian, 1608–1647) served as secretary to Galileo for three months, until Galileo's death. The Grand Duke of Florence appointed him to succeed Galileo as his personal mathematician and philosopher. Besides his work with atmospheric pressure, he improved the telescope and invented a primitive microscope.

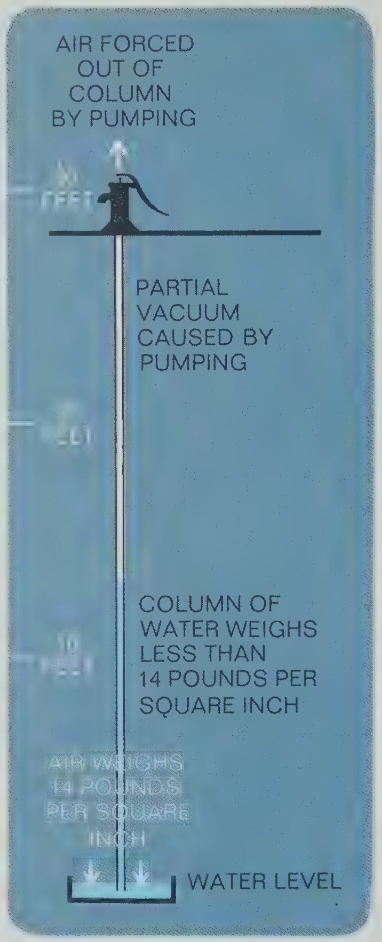


Figure 14-2 This diagram shows how air lifts water with the aid of a pump. However, no matter how complete a vacuum you can create with the pump, the water will not rise more than about 33 feet.

Figure 14-3 Atmospheric pressure on mercury and water is the same and will support the same weight of both. A column of mercury will be shorter than a column of water because it is denser.

14-3. Some of the mercury ran out of the tube, but most of it remained inside. Torricelli then measured the height of the column of mercury that remained in the tube. The column of mercury was 30 inches high. He found that the weight of this column of mercury was the same as the weight of a column of water about 33 feet high in a similar tube.

Torricelli then came to a daring conclusion. He reasoned that the column of mercury in the tube and the column of water drawn up by a lift pump were each supported by the

weight of a column of the atmosphere. The column of air pressed down on the surface of the mercury in the bowl and on the surface of the pool of water supplying the pump. What was daring about this reasoning was that Torricelli attributed weight to air. The physicists of his time believed Aristotle had been correct 2,000 years earlier when he stated that air did not have weight.

Torricelli kept his partly filled tube of mercury standing in the bowl of mercury. He observed that from day to day there were slight differences in the height of the mercury in the tube. He reasoned that these differences were caused by slight changes in the weight of the column of air pressing down on the mercury in the open bowl.

Since that time, meteorologists and other scientists have used tubes of mercury like Torricelli's to measure atmospheric pressure. These instruments are called **barometers.** The reading of the height of the column of mercury being supported by air pressure can be expressed in many different ways. The United States Weather Bureau originally measured the height of the column in inches. In 1940 it began to measure and report atmospheric pressure in **millibars** (mb). Most weather reports, however, still give the pressure in inches of mercury.

barometer; Greek: *baros*, weight + *metron*, measure.

millibar. A unit of atmospheric pressure equal to 1/1000 dyne per square centimeter.

Numerous weather stations now measure atmospheric pressure at various altitudes. From these measurements, it is possible to construct atmospheric-pressure maps for a certain altitude. Pressure maps show lines along which the atmospheric pressure is the same. These lines are called **isobars**. Figure 14-4 shows isobars that represent a pressure range from 1,016 millibars to 1,000 millibars.

14-2 STANDARD GAS PRESSURE

Shortly after Torricelli conducted his experiments, a French mathematician and philosopher named Blaise Pascal became interested in them. He reasoned that if Torricelli was correct in assuming that air pressure supported the mercury in a barometer, then the column of mercury should decrease on a high mountain. There should be less air above the barometer than near sea level.

To test this idea, Pascal's brother-in-law took a barometer to the summit of a mountain. He found that Pascal's idea was correct. The level of the mercury in the tube was about 80 millimeters lower at the top of the mountain than it was at the foot of the mountain. Thus, almost as soon as scientists

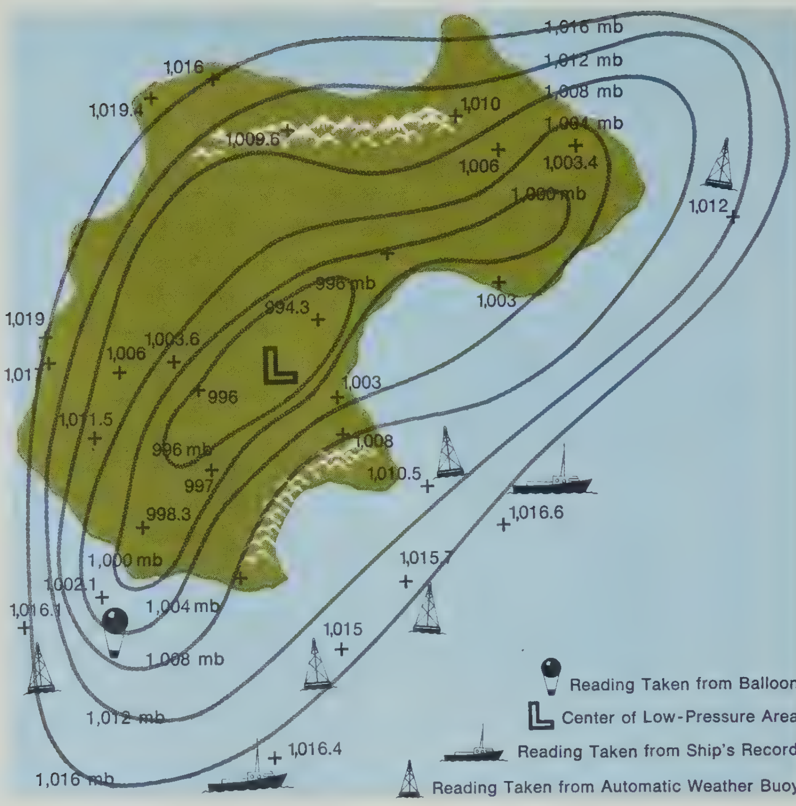


Figure 14-4 A meteorologist constructs a weather map that shows atmospheric pressure by a system of equal-pressure lines called isobars. Why does atmospheric pressure change as you move away from the center of low pressure?

learned that air had weight, they discovered that the pressure exerted by air varies from day to day and from place to place.

Scientists realized that measurements made on gases at one place could not be compared with measurements made at other places unless air pressure was taken into consideration. Actually, Robert Boyle, an English physicist, had started this trend of thought in 1660, when he showed that change in pressure changed the volume of a gas.

By 1801 Jacques Charles, a French physicist, had discovered that both pressure and temperature affect the volume of a gas. This understanding led scientists to adopt a standard pressure and a standard temperature for all information about gases. They adopted the pressure necessary to support a column of mercury 760 millimeters high as the standard pressure and 0°C as the standard temperature.

Chemists adopted 760 millimeters of mercury for the pressure standard because the atmospheric pressure at sea level averages 760 millimeters. Other scientists found that other units of gas pressure were more useful for them. Figure 14-5 shows what they are.

In honor of Torricelli, 1 millimeter of mercury at sea level and 0°C is called a *torr.*

Study Guide

1. What instrument is used to measure air pressure? Who invented it?
2. What factors induced Torricelli to study air pressure?
3. What Aristotelian idea was disproved with the invention of an air-pressure measuring device?
4. What is the greatest height of a column of water that can be supported by air pressure at sea level? What is the greatest height of a column of mercury?
5. Explain how the study of air pressure affects the study of all gases.

14-3 LOWS AND HIGHS

The first attempt to measure the atmospheric pressure regularly at many places and to report the readings daily to one place was probably made in the United States. This was done by the Secretary of the Smithsonian Institution, Joseph Henry, in the early 1850's. Such daily gathering of meteorological information was made possible by the invention of the telegraph. Henry's work at the Smithsonian Institution in Washington, D.C., brought into being the United States Weather Bureau.

The first man to use the kind of information gathered by Henry was Sir Francis Galton, an Englishman, who started weather mapping in 1863. Galton was a very able and most interesting man. He became an authority on weather and helped found the modern science of meteorology in the 1860's.

By studying worldwide weather reports, Galton discovered that there are zones where the atmospheric pressure is a little higher or a little lower than average. One of the zones that has a continually lower-than-average atmospheric pressure is the belt of the doldrums. This, as you recall, is the equatorial belt of rising, heated air (see Figure 14-7). Why should rising air create a low pressure?

The doldrums is a region where the average sea-level pressure is about 1,006 millibars (755 millimeters, or 29.7 inches). That is not much lower than the 1,013 millibars (29.9 inches) that is standard—but it is lower. In the region of the horse latitudes, where air is descending, the average sea-level pressure is about 1,020 millibars (30.1 inches).

The difference in pressure between the two zones of vertically moving air is enough to develop a flow of air from the region of higher pressure to the region of lower pressure.

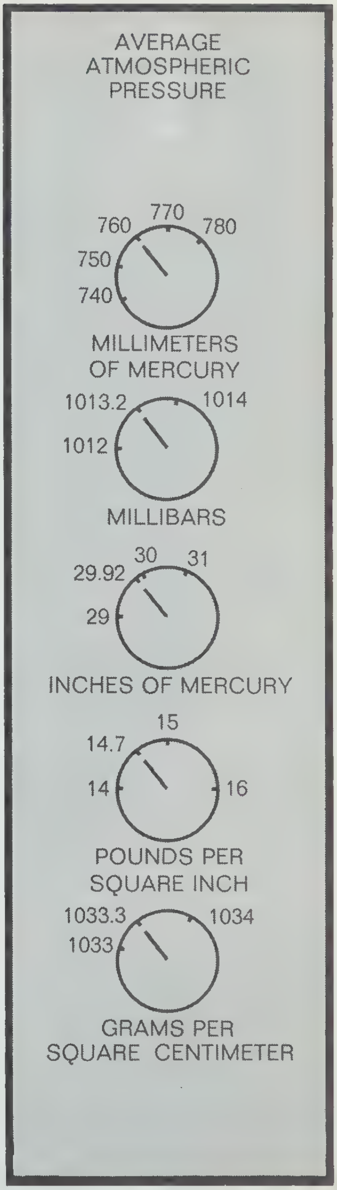


Figure 14-5 Scientists use different ways of expressing standard gas pressure. Chemists use millimeters of mercury; meteorologists use inches of mercury; earth scientists use millibars; engineers use either grams per square centimeter or pounds per square inch.

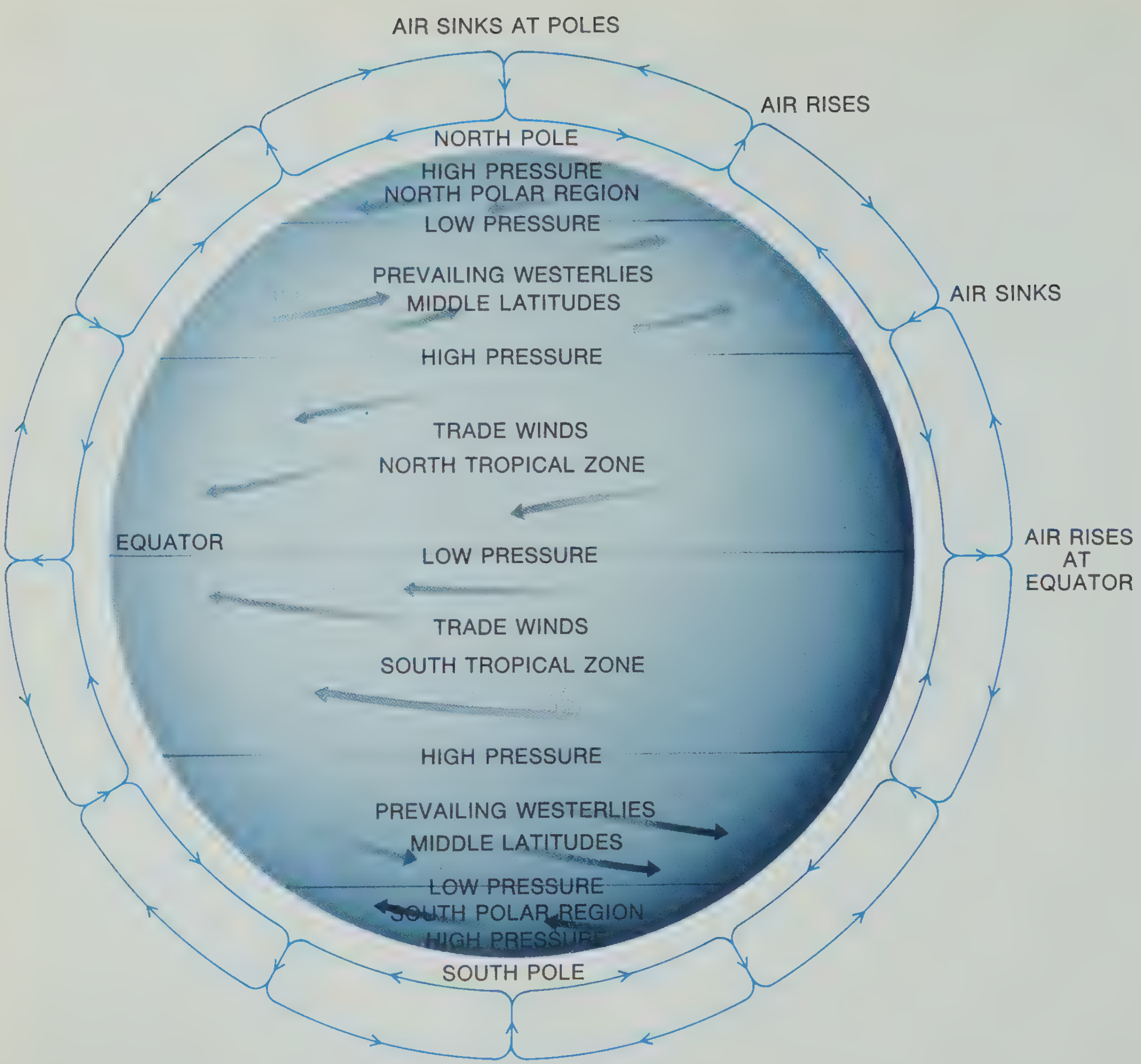


Figure 14-6 The world's pressure belts and air cells. You know what causes the low-pressure area around the doldrums. What would be responsible for the high-pressure area in the region of the North and South Temperate Zones?

Thus, the flow of air, or wind, is from the horse latitudes to the doldrums. These winds, as we have seen, are the trade winds. The direction of the trade winds is turned slightly to the right, or westward, in the Northern Hemisphere.

The best-developed tropical lows are located over the land, and the best-developed tropical highs are over the oceans. How does this fit into what we know about the factors that modify the characteristics of the atmosphere? What do we know about reasons for air being more dense or less dense? We know that the density of air at the surface of the earth is modified by its temperature, pressure, and humidity.

We know that throughout the year insolation is more or less uniform in the Tropical Zone. Is the heat produced by this radiation the same on land and sea? Because of its high specific heat, water absorbs and holds more of the incoming energy than does the land. What does this do to the atmosphere in contact with these surfaces in the tropics? The air in contact with the land is heated more than the air in contact with the ocean. This should make the air over the land warmer and less dense than the air over the ocean.

The tropics are a region of vast ocean areas and hot, humid lands. The atmosphere absorbs its limit of water vapor over both the ocean and the land. Therefore, the amount of water vapor in the air is governed by the temperature. Land temperatures in the tropics are generally higher than ocean temperatures. Why? This results in more water vapor per unit volume of air over the warm, humid land than over the ocean.

In the tropics, what is the difference in the combined effect of temperature and humidity on the density of air over land and air over the ocean? The higher temperature and greater humidity makes the air over the land less dense than the air over the ocean.

Figure 14-7 Sir Francis Galton (English, 1822–1911), a cousin of Charles Darwin, was best known for his work in heredity. He was the founder of mental testing. Besides his contributions to medical science, he made important contributions to meteorology and developed modern techniques of weather mapping.

14-4 THE WINDS ASSOCIATED WITH LOWS AND HIGHS

In Chapter 13 we noted that the surface flow of air in the great wind belts of the earth is disturbed. This occurs because the continents are not so smooth as the oceans, nor are they composed of uniform materials. Most of the Southern Hemisphere is ocean. Of the two large continents in the Southern Hemisphere, Africa has the less varied surface. South America has a long, high mountain range extending its entire length, and Africa does not. To avoid the complications introduced by the mountain range, we will turn our attention to Africa and see where the highs and lows are.

Figure 14-8 shows the high and low situation in January, the beginning of summer in the Southern Hemisphere. The African equatorial low is permanent and a strong one, well supplied by heated air and moisture. To the southwest of Africa lies the South Atlantic subtropical high, found in a high-pressure belt corresponding to the horse latitudes. To the southeast is the Indian Ocean subtropical high. There is a gradual change of pressure from each of the highs into the low.

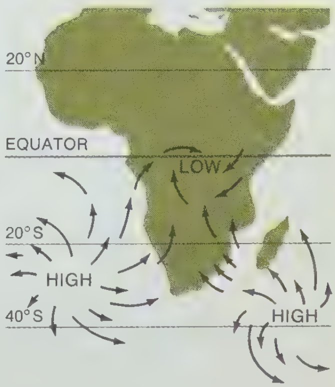


Figure 14-8 The lows and highs over the African continent in January, the beginning of summer in the Southern Hemisphere

In the area between a high and a low, the air must be moving in some direction. The air in a high, which is sinking toward the ground, will have to flow along the ground toward the area of the low, where it will begin to rise again. These movements of air along the ground between a high and a low are the winds that we experience every day.

The speed, or strength, of winds depends on the pressure gradient between the high and the low. The **pressure gradient** is the difference in pressure between two points, divided by the distance between them. The greater the pressure gradient, the stronger the wind.

Figure 14-9 shows the change of pressure. Air flows from the high into the low. Now turn back to Figure 14-8. Do the wind arrows point directly from the center of the high to the center of the low? Why not? What causes these arrows, indi-

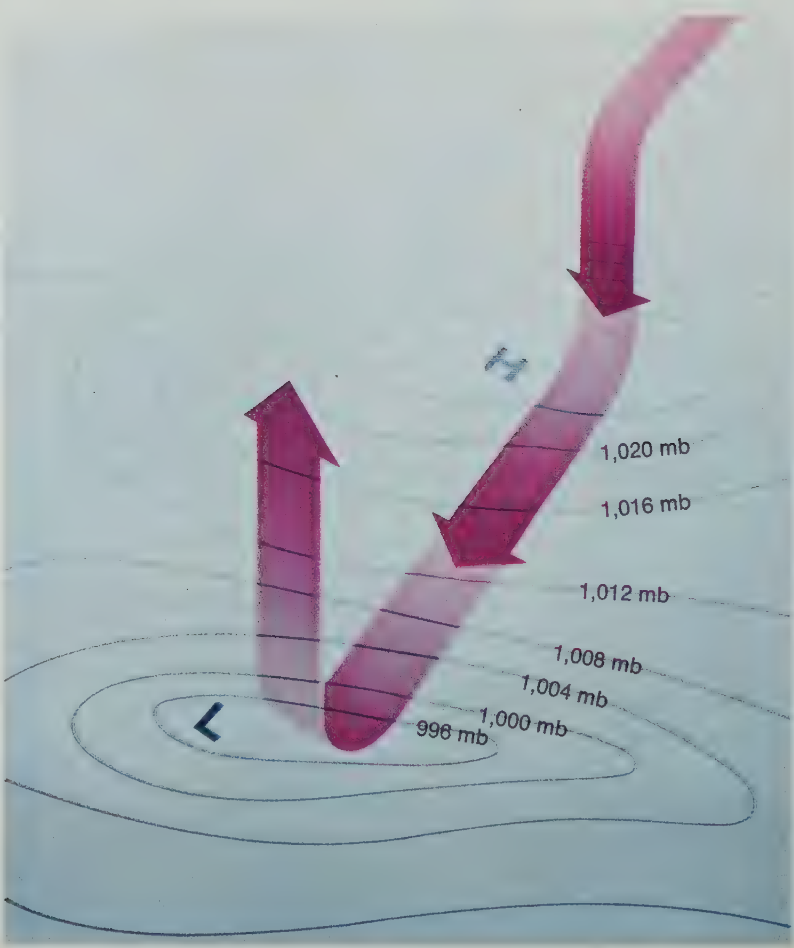


Figure 14-9 In a pressure gradient the winds blow outward from a high and inward to a low. The winds drop into the center of the high-pressure area and flow along the surface into the low-pressure area.

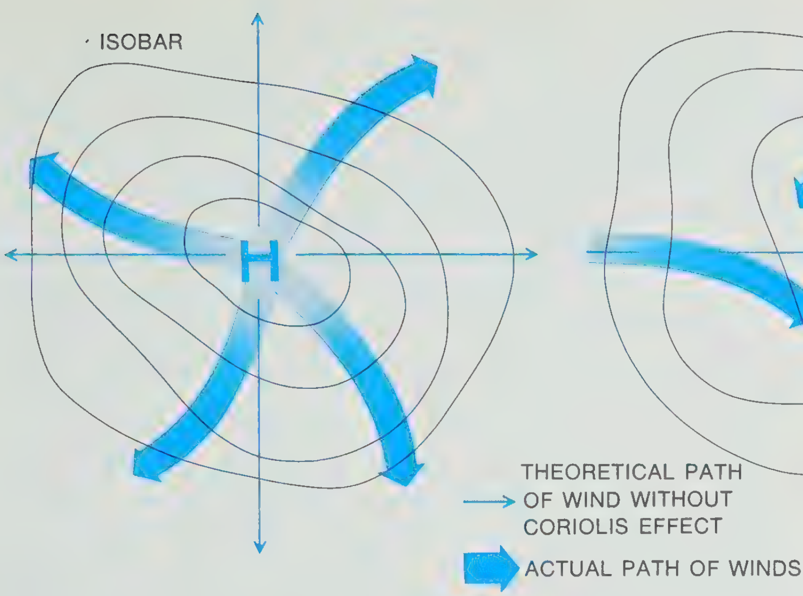


Figure 14-10 In the Northern Hemisphere the Coriolis effect causes winds to move not directly across isobars but toward the direction parallel to the isobars.

cating the wind direction, to be curved instead of straight? Why do the arrows around the highs curve more sharply toward the south than toward the north? The answer to these questions is explained by the Coriolis effect.

Without the Coriolis effect, air would move in a straight line from a high to a low (see Figure 14-19). However, the Coriolis effect acts at right angles to the pressure-gradient force, swerving the moving air to the left in the Southern Hemisphere and to the right in the Northern Hemisphere.

In Figure 14-8, notice that the few arrows marked on the map around the low suggest a clockwise flow. Why do we know so little about the winds around this particular low? The information used for this map has been gathered over the past fifty years. Why do we expect to have more and better information in the coming fifty years? Look at Figure 14-11, a photograph of a Tiros weather satellite. Now turn to Figures 15-11 through 15-15. Do these pictures supply part of the answer to that question?

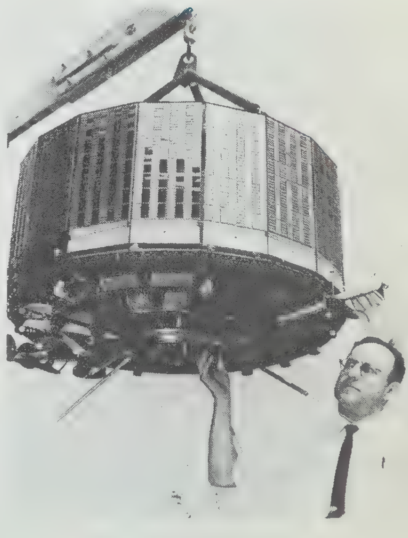


Figure 14-11 The National Aeronautics and Space Administration's weather observation satellite Tiros has wide-angle cameras and infrared experiment components. Satellites such as this have been able to track various weather patterns and storms.

Study Guide

1. What contributions did Henry and Galton make to the science of meteorology?

2. Explain why the trade winds blow.
3. State why land temperatures in the tropics are higher than ocean temperatures.
4. Explain why the air over the oceans in the tropics is denser than the air over the land.
5. Describe how highs and lows affect wind movement.
6. Write your own definition of a pressure gradient.

14-5 THE HIGHS AND LOWS OF NORTH AMERICA

Meteorologists use the term **cyclone** for any system of winds blowing in toward a low-pressure area. Therefore, the wind pattern around a low is called a **cyclonic flow**. An **anticyclone** is a high-pressure system. Winds circle out from an anticyclone.

Figures 14-12 and 14-13 show the general patterns of cyclones and anticylones associated with North America in January and in July. What are the principal differences in the pressure patterns at these two times? Why does a high-pressure area develop over the western states in winter and a low-pressure area develop in the same general region in summer? How can you relate this situation to the change in the amount of solar energy received?

Notice that in winter there are two well-developed maritime lows, one south of the Aleutian Islands and one south-

Figure 14-12 January average high- and low-pressure areas over North America

east of Greenland. No such well-defined lows exist in summer. Instead, there is a broad zone of slightly low pressure, which encircles the North Polar Zone. During the winter the low disappears over North America as the cold, polar air presses far into the United States. This movement of the polar air mass in winter isolates the two areas of low pressure over the warmer ocean water. Why does this happen?

You will find a clue to the answer in the different ways water, soil, and rock respond to incoming solar energy. Another clue is the effect of snow cover in the central Rocky Mountains and westward to the Pacific Coast. Would you expect snow to reflect more solar energy than open water does?

In Figures 14-12 and 14-13, try to find the prevailing westerlies, which you would expect to be present in the latitudes of the United States. Notice that the cyclonic winds into the lows and the anticyclonic winds out of the highs disturb the pattern of the prevailing westerlies. In the United States the pressure gradient between highs and lows usually has a greater influence on the local surface winds than do the prevailing westerlies.

Winds aloft, the ones that fliers at high altitudes must consider, are usually the winds produced by the rotational effect of the earth. Such winds are the prevailing westerlies and the

Figure 14-13 July average high- and low-pressure areas over North America

trade winds. Often when the sky is patchy with clouds in several layers, you can see the uppermost layer of clouds traveling with the prevailing westerlies. At the same time, the lower clouds are traveling in a different direction because they are influenced by local pressure differences.

Study Guide

1. What is an anticyclone?
2. Describe the relationship between incoming solar energy and the development of highs and lows.
3. Explain why winds at the surface of the earth can blow in a different direction from that of the winds aloft.

14-6 HURRICANES—SMALL-DIAMETER CYCLONES

Air moves from high-pressure areas to low-pressure areas. The velocity of the wind is related to the difference in pressure between two points. The greater the difference in pressure per unit distance, the greater is the velocity of the wind. **Hurricanes** are cyclones with a small diameter and a very great pressure gradient. Such a great change of pressure within a small diameter produces winds that exceed 75 miles per hour and are capable of causing great destruction. Figures 14-14 and 14-15 show a hurricane and the records of its atmospheric pressure.

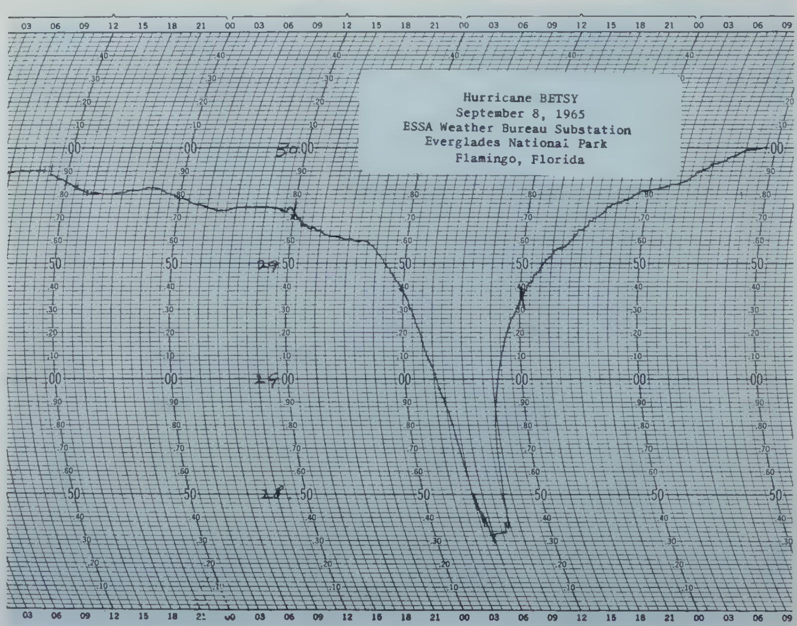


Figure 14-14 A barometer in Everglades National Park, Florida, recorded the air pressure associated with this hurricane. What was the air pressure at 6 A.M.?

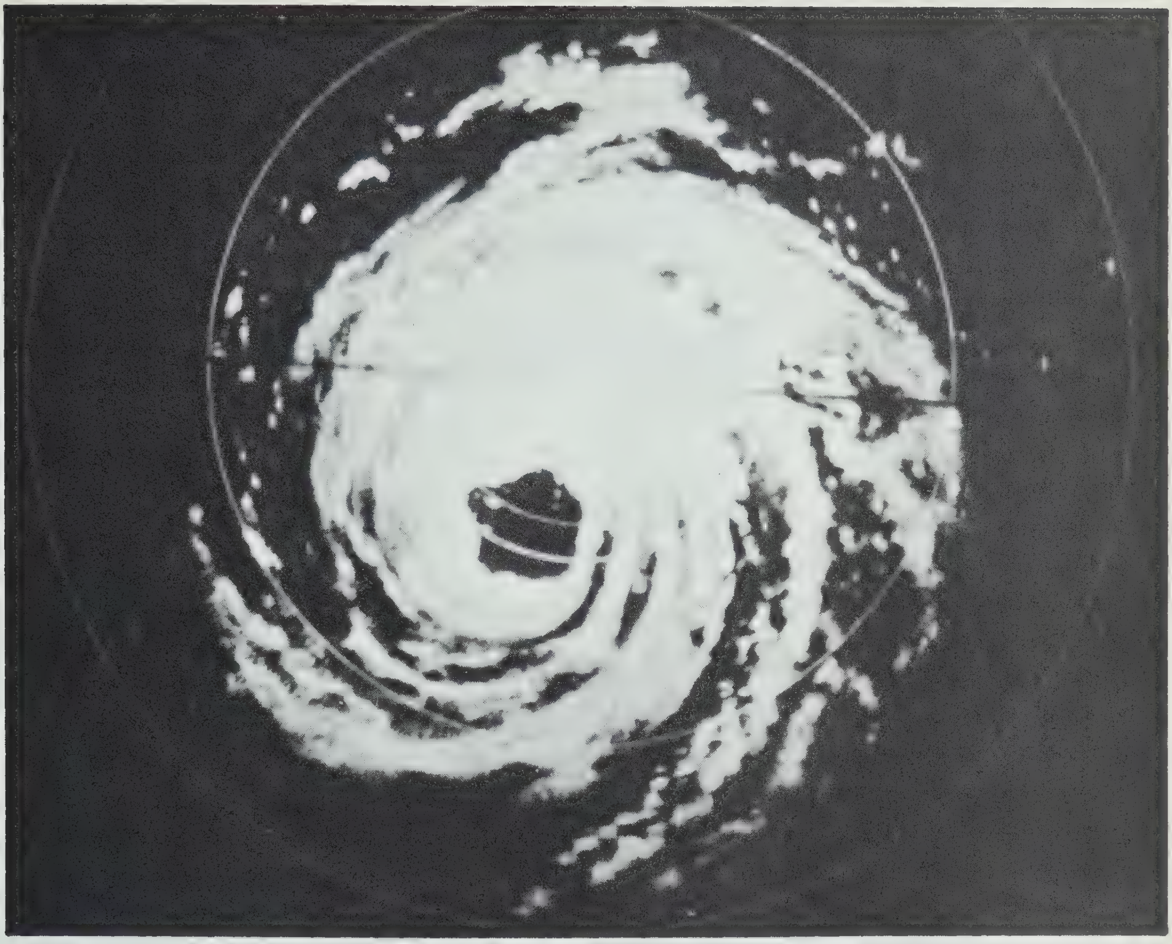


Figure 14-15 In the early morning of September 8, 1965, Hurricane Betsy passed a few miles west of Miami, Florida. Notice the clear central eye surrounded by an area of rain (white).

Through the efforts of a small number of courageous fliers and scientists, we now know much about hurricanes. The hurricane hunters of the United States Air Force, Navy, and Weather Bureau fly out into the tropical Atlantic Ocean, where hurricanes form. Once these men locate a hurricane, they fly with it and plot its course and wind speeds. They radio this information to the Hurricane Center in Miami, Florida, which broadcasts warnings days before the hurricane reaches inhabited places.

14-7 THE STRUCTURE OF A HURRICANE

Hurricanes, as shown in Figure 14-14, are rarely more than 300 miles in diameter and have an eye, or center, from 5 to 20 miles across. In the eye there is almost a total calm and no

rain. This is the area of rising air. The barometer may read as low as 937 millibars (27.6 inches) in the eye. Outside the eye the winds reach velocities of between 75 and 200 miles per hour.

Although the winds in the hurricane may circle at more than 100 miles per hour, the hurricane itself moves much more slowly. The eye of the hurricane travels along its path at a speed of 5 to 20 miles per hour. This means that the hurricane patrol can warn most places far enough in advance to protect life and property from the force of the winds.

The rain that falls from a hurricane is torrential. This occurs in the belt of high winds that surrounds the quiet eye. Because of the winds, it is impossible to catch all the rain that falls over a rain gauge. The best guess is that the rain may fall at a rate of 24 inches a day. That is a lot of rain!

Storms like hurricanes are generated at both edges of the belt of the doldrums. Because the equatorial heat belt lies almost entirely north of the equator, most cyclonic maritime storms are generated in the Northern Hemisphere.

14-8 HURRICANES IN ACTION

Our hurricane season reaches its peak in August and September. Hurricanes start in the Atlantic Ocean between North Africa and the West Indies. For some unknown reason, a disturbance forms in the belt of the trade winds. This disturbance is carried along by the currents of air as an eddy is carried in a river.

Air begins to flow into the disturbed region from all sides, and as it does so, it rises. Clouds form, releasing latent heat energy, which helps to power the storm. (Do you remember where the latent heat energy comes from?) More air flows into the area, and the mass of air slowly starts to revolve in a counterclockwise direction. Strong updrafts develop. The rising, humid air is cooled, producing very heavy rain. It is this rain that is detected on the radar of a hurricane-hunting aircraft. Through a complicated chain of events, heat energy is changed to kinetic energy, causing the high winds of the hurricane (see Figure 14-16).

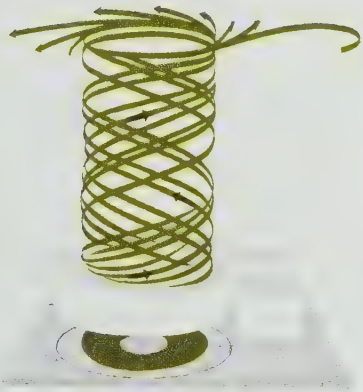
After sweeping across the Caribbean Sea, the hurricane usually heads for the mainland of North America. The high winds, the heavy rain, and the flooding by high waves and extra-high tides make hurricanes among the most destructive of storms.

Florida most frequently takes the brunt of the howling winds. The farther north the hurricane moves, the more it is

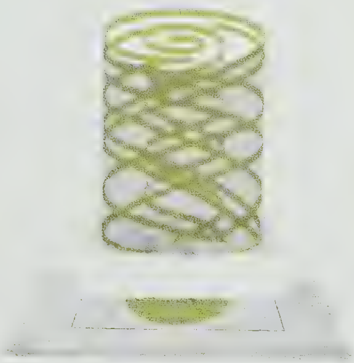
Figure 14-16 The birth and decay of an Atlantic hurricane

(1) Warm, moist easterlies of the hot, late summer are the origin of hurricanes.

(2) A low-pressure area disturbs the easterlies, giving them a twisting motion. In that area, air starts to pile up, ascending to 40,000 feet.



(3) The rotation of the earth gives more twist to the rising column of air. The condensation of warm, moist air gives energy to the now spinning column of air.



(4) As the hurricane moves over land or cold water, it no longer receives energy to maintain its strong winds. The violently twisting winds abate, and the eye fills in with clouds.

turned to the right by the Coriolis effect. Thus, it usually moves northeastward, following the edge of the Bermuda-Azores high-pressure area. As the hurricane moves over colder water, it loses its source of energy. In spite of this general pattern of hurricane paths, high- and low-pressure areas may force it into the Gulf of Mexico and the surrounding land.

Similar winds on the western margin of the Pacific Ocean wreak damage from the Philippines to Japan. Such storms are similar to hurricanes, but there they are called **typhoons.**

How much energy is in an average hurricane? The total energy in a hurricane is estimated at 4×10^{17} calories. It is equal to the energy obtained by burning 70 million tons of coal. To us, these are just very large numbers—too large for most of us to comprehend.

This amount of energy, however, is only a small amount of the energy the earth receives from the sun in a day. An average hurricane contains only one ten-thousandth of that amount of energy. A hurricane receives that solar energy in the heat belt of the tropics. It moves most of the energy northward, releasing it in regions that receive less solar energy. Hurricanes help to distribute the excess energy received in the equatorial regions to other regions.

Study Guide

1. Does air move out of a low-pressure area, or a high-pressure area?
2. Explain what is meant by a great pressure gradient.
3. Where are hurricanes formed?
4. Why do hurricane winds take a counterclockwise direction in the Northern Hemisphere?
5. What is the eye of a hurricane?
6. What is the source of a hurricane's energy?

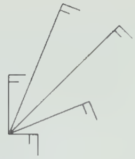
SUMMARY

Torricelli's discovery of a way of measuring air pressure made possible the study of the physics of the atmosphere. Through the work of Henry and Galton, modern meteorology came into being. Galton's discovery of zones where the sea-level air pressure is a little higher than in other adjacent areas explains the origin of winds. Wind is air moving from a high-pressure area to a low-pressure area. Continued observation of air pressure in relation to storms gave rise to the concept of local areas of high and low pressure.

In the Northern Hemisphere the Coriolis effect causes air flowing into a low-pressure area to move to the right in the direction of flow. Such a wind pattern is called a cyclone. Air circles out and away from a high. To distinguish this opposite movement of the air, highs are called anticyclones. The most destructive winds we know are associated with lows, in which there is a very great pressure gradient. These destructive winds are known as hurricanes and typhoons.

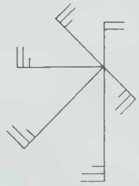
REVIEW AND DISCUSSION QUESTIONS

1. Why do you think 200 years elapsed between Torricelli's invention of the barometer and the understanding of the dynamics of winds?
2. A "Cape Cod barometer" can be made by half-filling a bottle with colored water and stoppering it with a cork through which one end of a U-shaped glass tube is inserted. When the bottle is inverted and hung on the wall, it will register changes in air pressure. Why?
3. Why was it necessary for physicists and chemists to adopt a standard temperature and a standard pressure for use in studying the characteristics of gases?
4. An altimeter is an instrument used to measure height above sea level. It depends on air pressure to move the needle that indicates altitude. Explain why this instrument is only reasonably accurate for measuring altitude.
5. On still winter nights in the foothills of snow-covered mountains, cattle and wildlife tend to gather on the ridges and not in the valleys. Give your explanation for this.
6. Although hurricane winds reach velocities of more than 100 miles per hour, the hurricane itself rarely moves along its path faster than 20 miles per hour. Explain this curious situation.
7. Each of the accompanying diagrams is called a *wind rose*. These are used on charts to report the frequency with which winds blow from particular directions during particular periods of the year. Study the three wind roses, and from what you know about the great wind belts, suggest the belt in which the reporting station is located.
8. Explain how you can estimate the location of a local low in your area of the United States.



STATION A
JUNE
3% CALM

STATION B
JUNE
32% CALM



STATION C
JANUARY
3% CALM

CHAPTER 15

STORMS CROSS OUR CONTINENT

Thus far, discussion of the physics of the atmosphere has been very general. Now we shall study some of the practical applications that can be made of this knowledge. The prediction of our daily weather is probably the most useful.

By studying the movements of cyclones and anticyclones across the country, meteorologists have learned that certain patterns of these movements usually result in certain kinds of weather. They base their predictions on these patterns. This is also why the predictions are not always accurate. We just do not know enough about all the factors acting in our atmosphere to make completely accurate predictions.

15-1 FRONTS

As you read in the previous chapter, we do not know precisely how a hurricane starts. This is true of all storms. We know that storms are associated with lows. We also know much about storms once they have started.

Lows that become storms are associated with fronts. A front is the boundary between two air masses that differ in density. Since the density of air depends very largely on its temperature, a front can be thought of as a boundary between air masses of different temperatures. Cold air masses usually come from such regions as central Canada or Siberia, where it is cold and dry. These air masses are dense because they are both cold and dry. Warm air masses usually form over tropical oceans. Such air masses are less dense than cold air masses because they are both warm and moist.

Fronts move from a region of higher pressure toward a region of lower pressure. In the United States they tend to move from west to east under the influence of the Coriolis effect—the same effect that causes the prevailing westerlies. Terrain features, such as the great north-to-south mountain

Man has devised instruments to measure the factors that make up the weather.

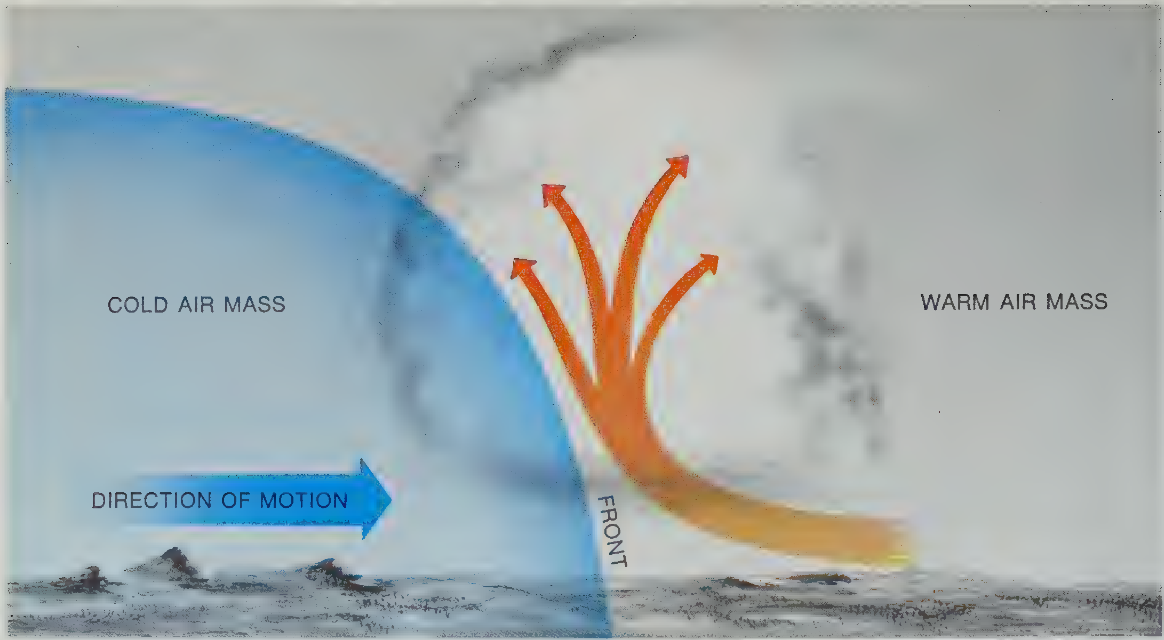


Figure 15-1 An advancing cold front forces a warm air mass to rise by wedging under it. Thunderstorms and rain usually accompany a cold front.

ranges, influence the path taken by a front. The broad Mississippi Valley acts as a trough, through which fronts move unaffected by terrain.

Usually the line of a front is moving. If a cold air mass is advancing into a territory covered by warm air, we call it a **cold front**. If the reverse is true, we call it a **warm front**. A cold front and a warm front are shown in Figures 15-1 and 15-2 respectively. If neither air mass is invading the region of the other, the line is called a **stationary front**. The line of a front is usually smoothly curved or even straight. When this smooth line is disturbed, a cyclonic storm may develop.

15-2 A STORM BREEDER

The meeting line between two air masses can take still a fourth form. In this type of front, an **occluded front**, a complex set of conditions has led to its formation. An occluded front starts as a stationary front, which develops into both a cold and a warm front (see Figure 15-3). For some reason, the cold air mass starts to move southward and form a cold front. Adjacent to this, the warm air mass begins to move northward as a warm front. This produces a wave in the originally smooth line of the stationary front. As the advancing cold front speeds up, it pivots at the point where it meets the warm front.

Figure 15-2 The warm front has a gentle slope, with continuous drizzle or light rain over an area of about 200 miles. In the winter a warm front may cause an ice storm.

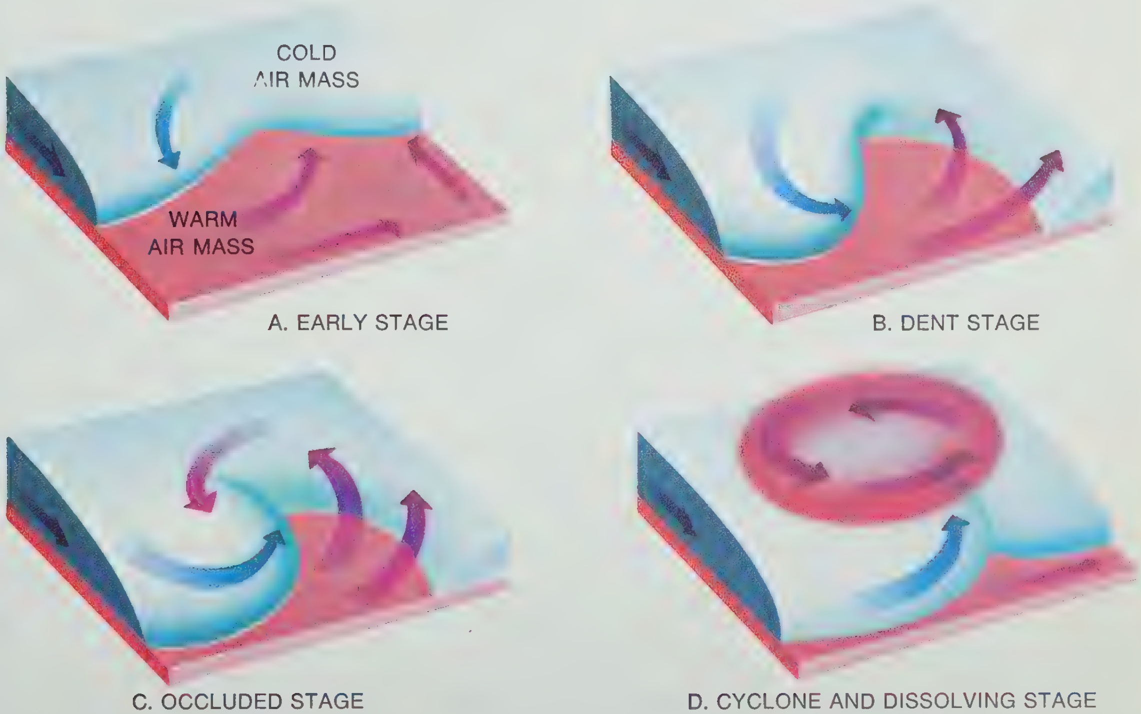


Figure 15-3 When a strong cold front overtakes a slow-moving warm front, the cold air masses on both sides meet and force the warm air masses aloft. The result is an occluded front. There is never a sharp front between the two systems, and the clouds are characteristic of both warm and cold fronts.

In about 24 hours the cold front turns so far around that it slips under and lifts a large volume of the warm, moist air. When the pivoting cold front joins the cold air mass that has been north or east of the warm front, the occluded front is formed.

An occluded front differs from all others. It does not come in contact with the ground. Instead, it is the boundary between the cold air along the ground and the warm air above the ground.

As the occluded front is forming, warm, moist air blows into the deep dent in the original stationary front. The sides of the dent are not parallel but converge toward the pivot around which the cold air is turning. The advancing air from a warm, high-pressure area is trapped between the converging walls of cold air. It cannot penetrate the cold air mass. The only thing it can do as it advances into the dent is to rise. This rising, warm air produces a low-pressure area.

The physics of the situation is complex. You can understand that a deep column of warm, moist air must be lighter than a similar column of cold, dry air. Therefore, a low-pressure area probably forms under the rising air. The Coriolis effect would give a circular motion to the rising air, forming a cyclone. Adiabatic cooling of the spiraling, rising air would cause condensation and the formation of clouds. This process releases the latent heat of evaporation from the water vapor. The released energy increases the velocity of the winds, and a storm develops. Depending on the temperature, it will either rain or snow.

Study Guide

1. What is an air mass?
2. What is a front?
3. How might you tell whether a front has passed over your town?
4. What is the main difference between cold and warm fronts and a stationary front?
5. Describe how a wave forms in a smooth front between air masses.
6. If air rises in an occluded front, what might you expect to happen to the weather?

15-3 THE WEATHER MAP

One of the best ways to watch the movement of weather across the country is to study the daily weather maps found in most newspapers. These maps show the temperature, the wind direction and velocity, the precipitation occurring at a

Figure 15-4 Synoptic (general view over a broad area) weather maps are plotted in one of the offices of the United States Weather Bureau.

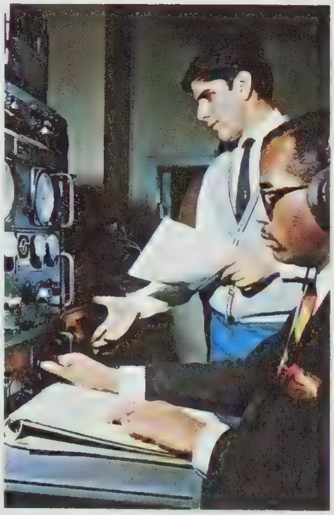


Figure 15-5 Teletype, computers, and plotting machines are used to collect data from weather stations around the country. The data is assembled daily at the National Meteorological Center, part of the U.S. Department of Commerce, Weather Bureau.

weather station, and the location of highs, lows, and fronts. The daily maps are prepared by the United States Weather Bureau and are simplified versions of the detailed maps prepared for use by professional meteorologists. Figure 15-4 shows the preparation of a weather map. Since most of you will never see a detailed map, we will use in our discussion the simplified, newspaper weather maps.

A weather station, which can be a simple shack or a shelter, contains instruments that continuously record the weather conditions. These instruments are read at regular intervals, usually every three hours, and the data soon reach the National Meteorological Center, in Maryland (see Figure 15-5). There, all the data are compiled, and plotted on blank weather maps; then the forecasts are made. The data are received from manned weather stations, weather balloons, radar stations, high-flying aircraft, and weather satellites such as Nimbus, Tiros, and the Environmental Survey Satellite (ESSA).

The symbols used on weather maps to report data are easy to learn. The legend in Figure 15-6 shows what they mean. As you can see on the map in Figure 15-7, atmospheric pressure is shown by isobars (see Section 14-1). From the pattern of isobars, you should be able to locate the centers of highs and lows. How are they shown? At the end of each isobar is a number showing the pressure in inches of mercury. Generally, over 30 inches is considered high pressure and below 30 inches is considered low pressure. However, the terms *high pressure* and *low pressure* are relative terms.

Figure 15-6 These are the standard symbols used in the legends of all weather maps.

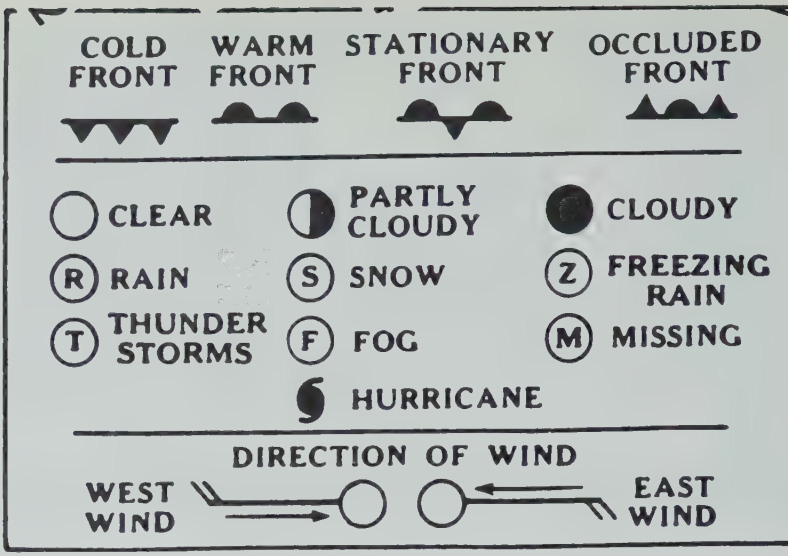
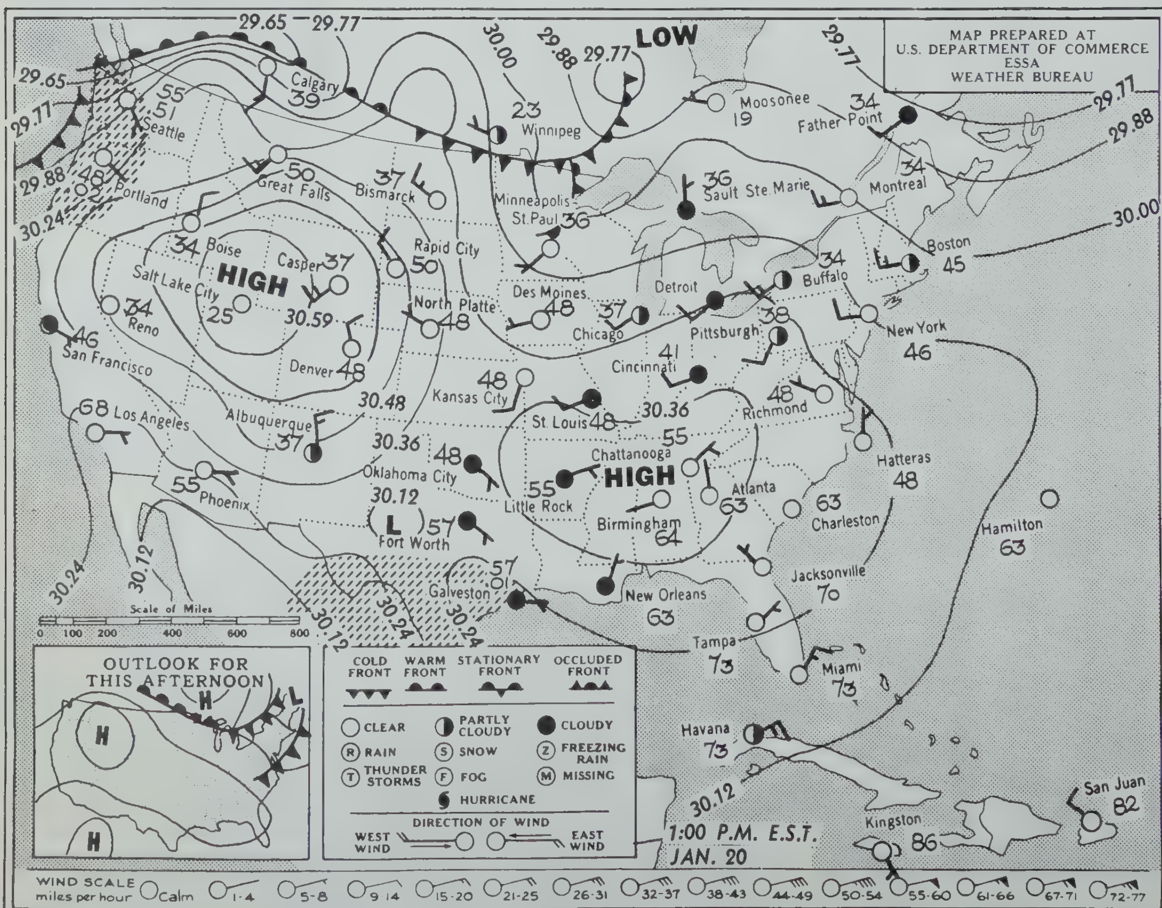


Figure 15-7 A daily weather map for January 20. Using the symbols in Figure 15-6, describe what the weather in your area was like on this day.



Fronts are indicated by heavy solid lines, with symbols on one or both sides of the lines. Look at the legend to learn the symbols for the four types of fronts.

Each weather station is represented by a circle. The symbols within the station circles indicate the condition of the sky when the data were collected. The number next to the station circle is the temperature in degrees Fahrenheit at the time the station reported.

Attached to each station circle is a **wind arrow**. It points in the direction from which the wind is coming. Attached to the arrow at an angle may be one or more short lines. As you can see from the legend, a very short line represents a wind velocity of about 5 miles per hour. A longer line represents a wind velocity of about 10 miles per hour. By combining long and short lines, the wind velocity within 5 miles per hour of its true velocity can be reported. For a wind of 50 miles per hour, a small flag is used.

The wind direction is measured by a **wind vane**, which points in the direction the wind is coming from. The speed of the wind is measured by an **anemometer**. Both these instruments are shown in Figure 15-8.

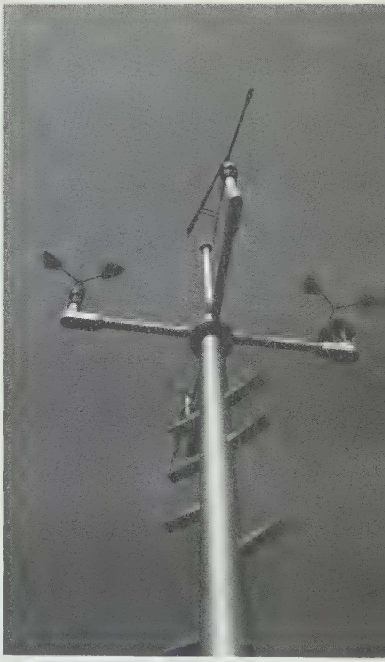


Figure 15-8 Anemometers and wind vanes are instruments used by meteorologists to measure wind velocity and direction.

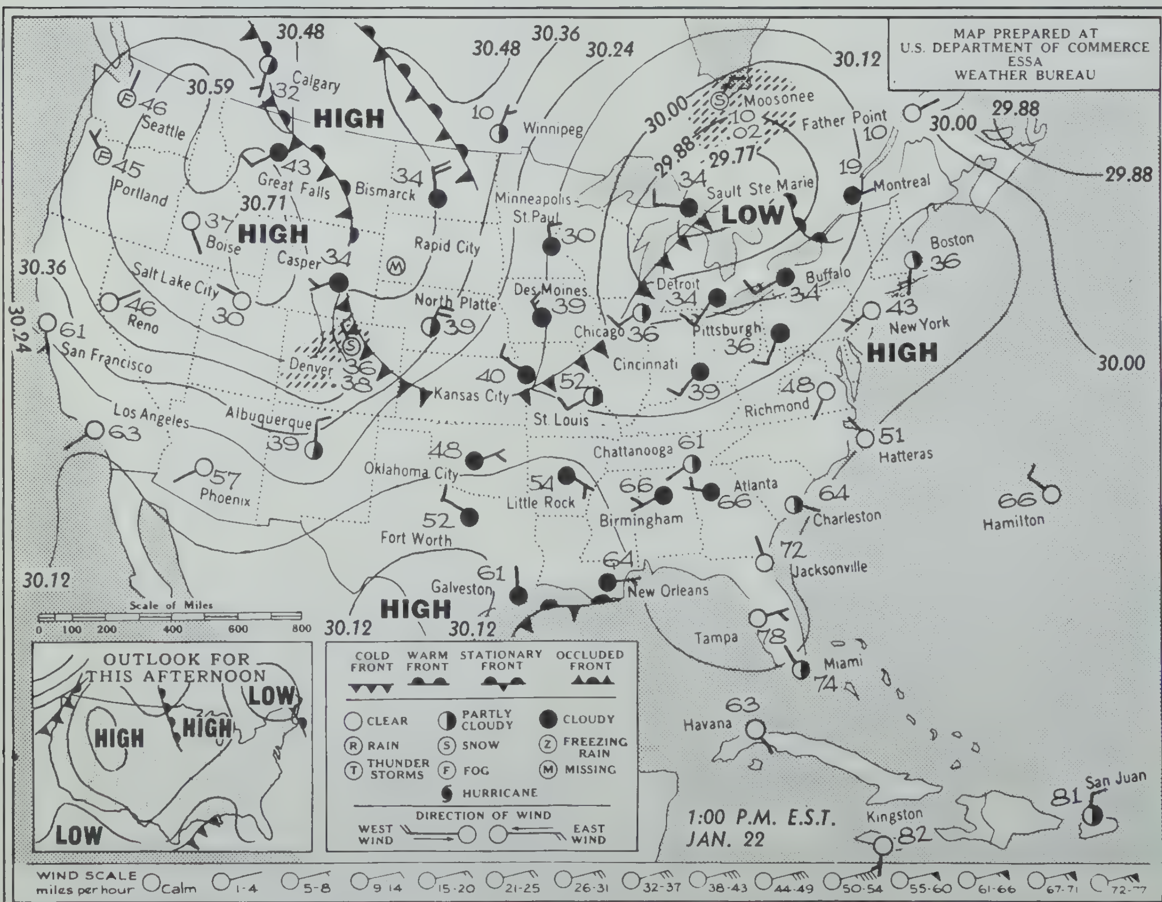
15-4 TRACKING A STORM

The weather maps for the five days beginning January 22, 1968, are shown in Figures 15-9 through 15-13. Above each map is a photograph of the United States taken on the same day but at a slightly different time. These photographs were taken by the ESSA weather satellite from a height of 890 miles. On the photographs, try to locate the air masses and fronts shown on the weather maps.

We will start our analysis of five days of winter weather in the United States by carefully examining the weather conditions on Sunday at 1:00 P.M. (Eastern Standard Time) on the East Coast. What time was this in the region where you live? Notice that in the areas of precipitation (shaded on the map) the winds are blowing inland from offshore. This maritime air is relatively warm and moist. As it rises over the cooler, drier continental air, it condenses and causes precipitation.

The important pressure system on Sunday's map is the low over Manitoba, Canada, north of Winnipeg. By Monday the low has moved over the Great Lakes, a distance of 800 miles. Between the low and the western high is a cold front. The front dips into Kansas and Missouri; it becomes a stationary

Figure 15-9—15-13 Daily weather maps, and corresponding weather photographs taken by the ESSA weather satellite, from Sunday, January 22, through Wednesday, January 26



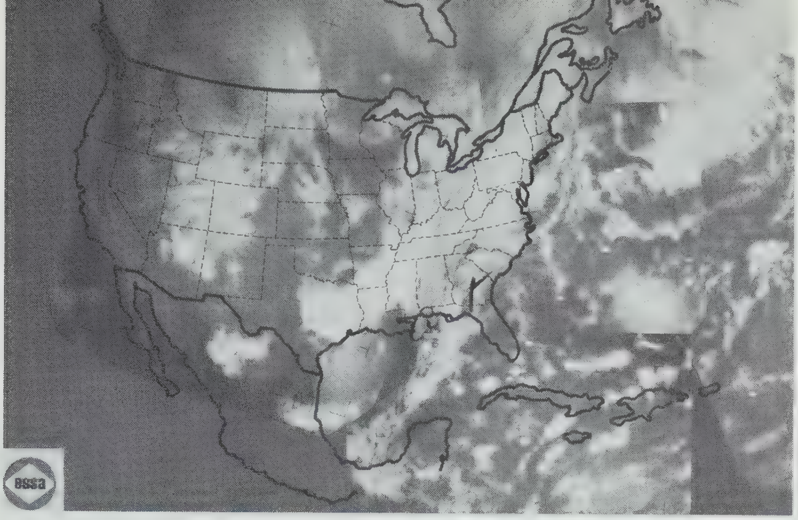
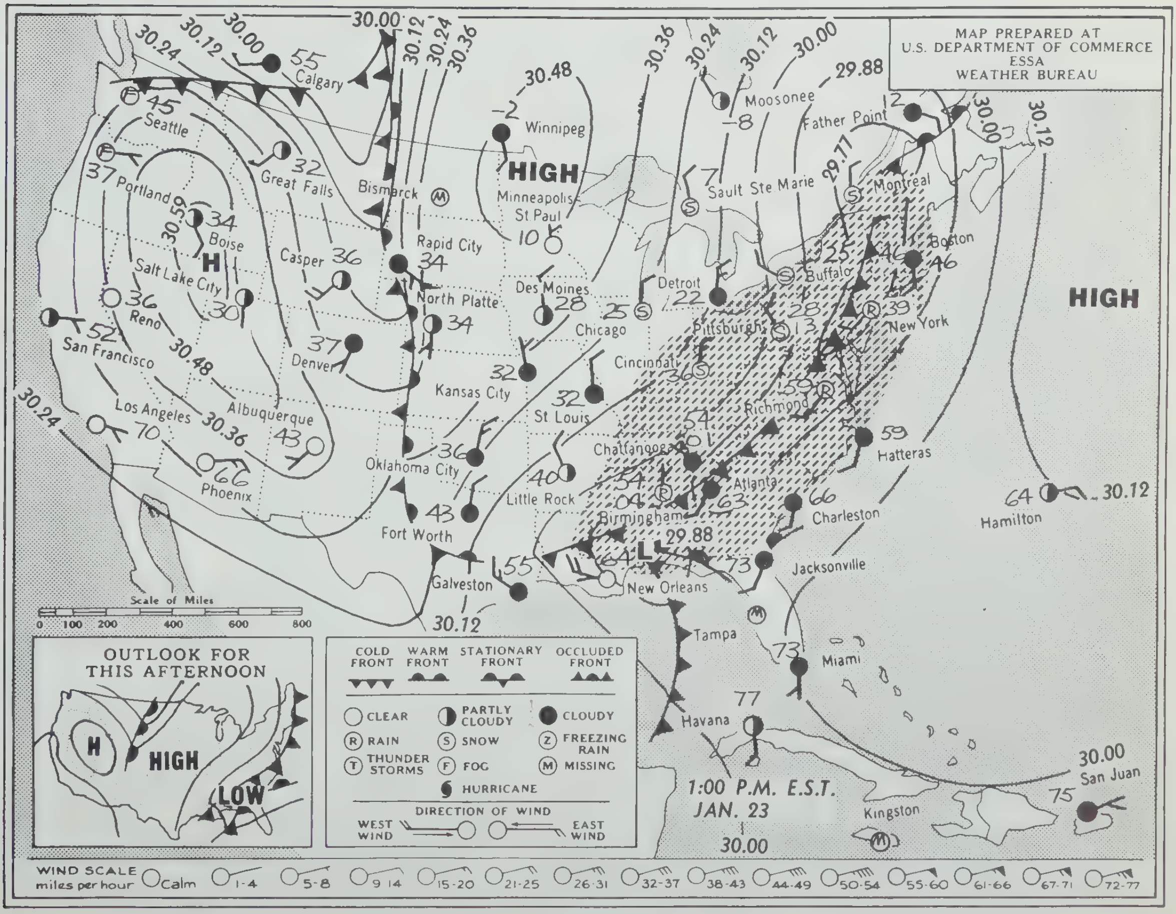


Figure 15-10 Monday, January 23



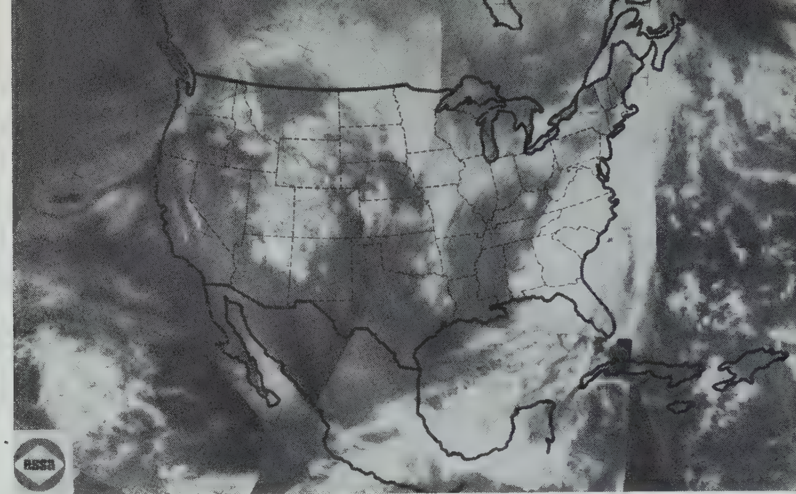
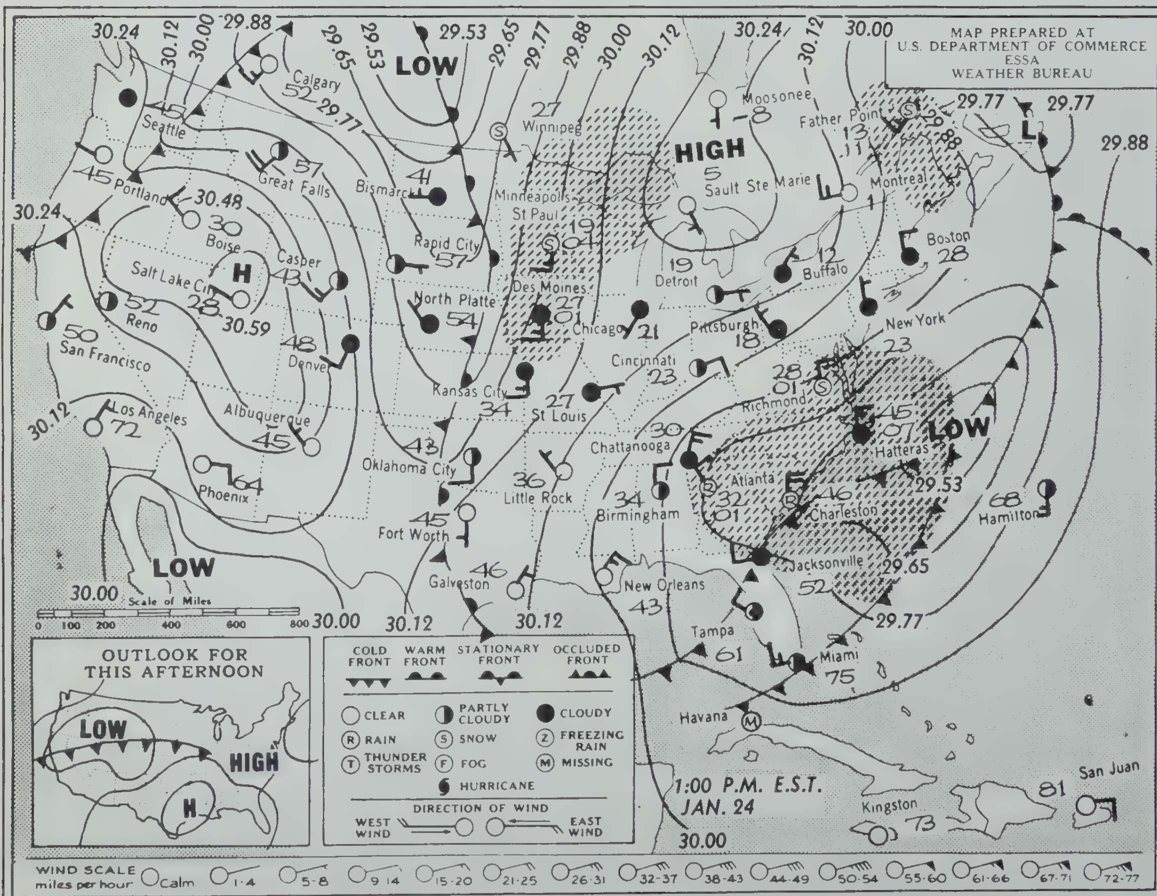


Figure 15-11 Tuesday, January 24



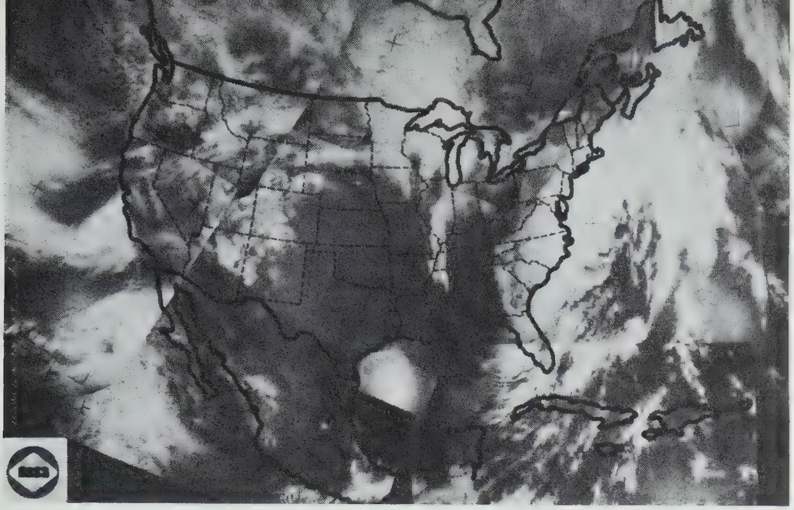
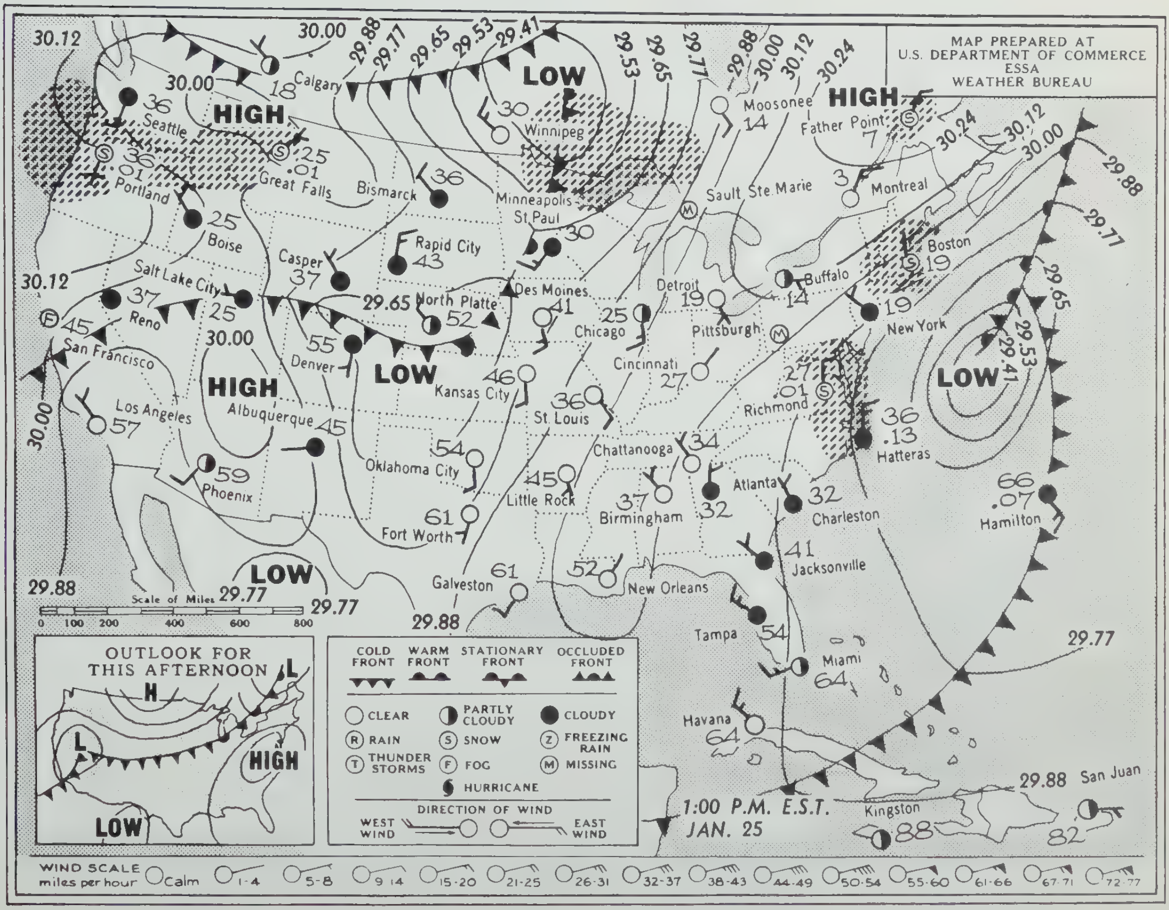


Figure 15-12 Wednesday, January 25



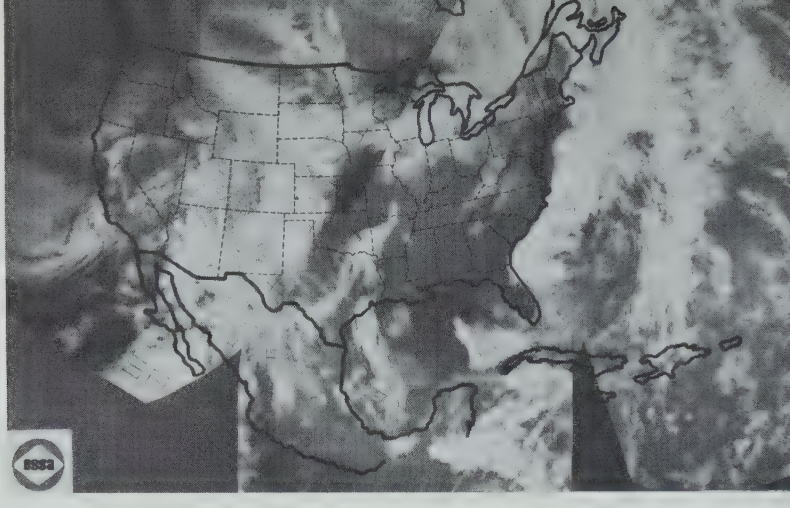
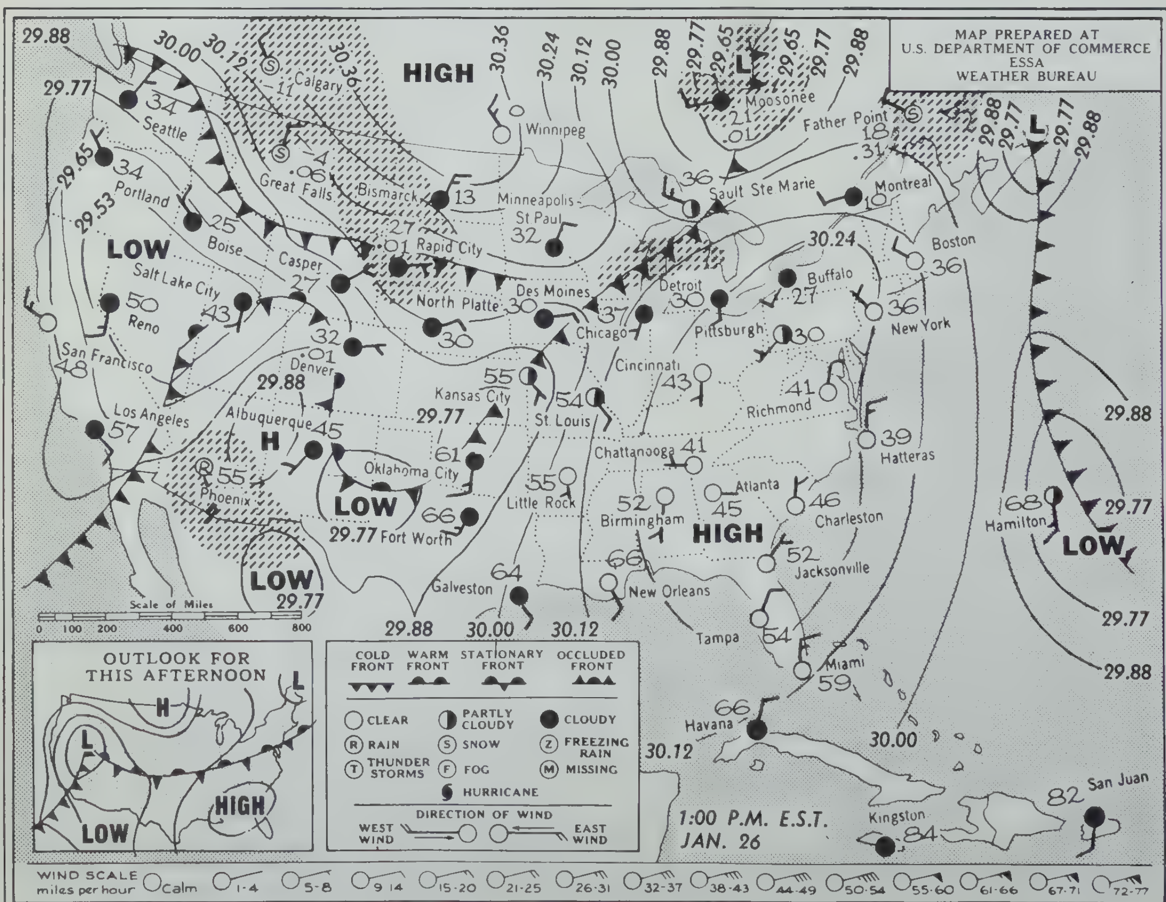


Figure 15-13 Thursday, January 26



front in the Northwest. The cold front represents the leading edge of a mass of *cP* air from Canada. It has pushed down into the middle of the United States, bringing cold, dry air —the normal condition in winter.

The two highs that on Sunday were south of Hudson Bay and over Mississippi have joined together by Monday to form a **high-pressure ridge** all along the Atlantic Coast. That ridge will play an important role in the next day's weather.

As the ridge continues to move out to sea under the influence of the prevailing westerlies, the air picks up large amounts of moisture. This moist air then follows the local pressure gradients. It moves westward from the high-pressure ridge toward the region of lower air pressure over the land.

While the ridge of high pressure is moving out to sea, the low that had been over the Great Lakes on Monday has drifted to the east. By Tuesday it has spread out to produce a **low-pressure trough** along the Appalachian Mountains, from Maine to Mississippi. Why do you think meteorologists use the term *ridge* for a linear high and *trough* for a linear low?

The air west of the trough is cold, *cP* air. All along the Atlantic Coast it meets the warmer, moist air moving in from over the ocean. The result is widespread rain and snow all along the eastern seaboard. On Wednesday and Thursday a coastal cyclone develops off the East Coast.

While all this activity on the coast has been occurring in the *cP* air mass, a new high has formed over Minnesota (see Tuesday's map). The winds in this high-pressure air mass have pushed the cold front you saw on Monday's map all the way to the Gulf Coast. Notice the difference in temperatures on either side of that front. The meeting of the cold front and the warm air over the Gulf Coast contributes to the precipitation occurring there.

Cutting across Tuesday's map, from Alberta, Canada, to Texas, is a stationary front. Just west of it, a new low-pressure trough is forming. On Wednesday's map this young trough has moved eastward. On Thursday two weak low-pressure centers have formed in the trough. Notice how the movement of the air masses pushes the cold front across the southeastern states. Look at the temperatures reported at Charleston, South Carolina. Notice how these temperatures change during the three days it takes for the cold front to pass.

Study Guide

1. How would the following winds be shown on a weather map?
   a. Wind from the west at 12 miles per hour

b. Wind from the southeast at 3 miles per hour
c. Wind from the south at 23 miles per hour
d. Wind from the northeast at 80 miles per hour

2. Answer the following questions based on Figure 15-11.
   a. What kind of front lies over the ocean east of Boston and New York?
   b. Where do you find a stationary front?
   c. What is the atmospheric pressure at Chicago, Illinois?
3. Answer the following questions based on Figure 15-9.
   a. There is a short warm front from Hudson Bay toward Lake Ontario. What is the range of temperature difference on either side of that front?
   b. What were the weather conditions at Seattle, Washington, at the time the map data were collected?
4. Approximately how many miles per day does a cyclone travel?
5. What is a low-pressure trough? a high-pressure ridge?

15-5 STABLE AND UNSTABLE AIR

If an air mass is to produce violent or unpleasant weather, it must be able to release its energy rapidly. We call such an air mass **unstable.** The opposite, of course, is an air mass that is **stable.** A stable air mass does not release its energy rapidly, and therefore does not cause violent or rapid changes in weather.

Meteorologists are always interested in determining whether an air mass is becoming more stable or more unstable. There are several factors that control this. If a mass of air is warmer than the land over which it passes, the earth will absorb heat from the air. The lower air will thus become cooler because of loss of heat. This mass of air is becoming more stable. For this reason, the moisture in stable air does not have much of a chance to rise, cool, and condense. Thus, rain will generally not occur under these conditions. Sometimes, if the humidity is high enough, stable air can produce fog, mist, and low clouds.

Unstable air tends to rise. If a polar air mass is cooler than the surface over which it passes, the air will absorb heat from the surface. The lower air will then become warmer and begin to rise. The upper air remains cool. The adiabatic cooling, which results from rising air, increases the chance of precipitation. This *overturning* of the air tends to make it clear and free of pollution.

The moisture content, temperature, and other factors all determine whether an air mass is stable or unstable. It is the

energy from the condensing water vapor in unstable air masses that is largely responsible for the unpleasant weather they cause.

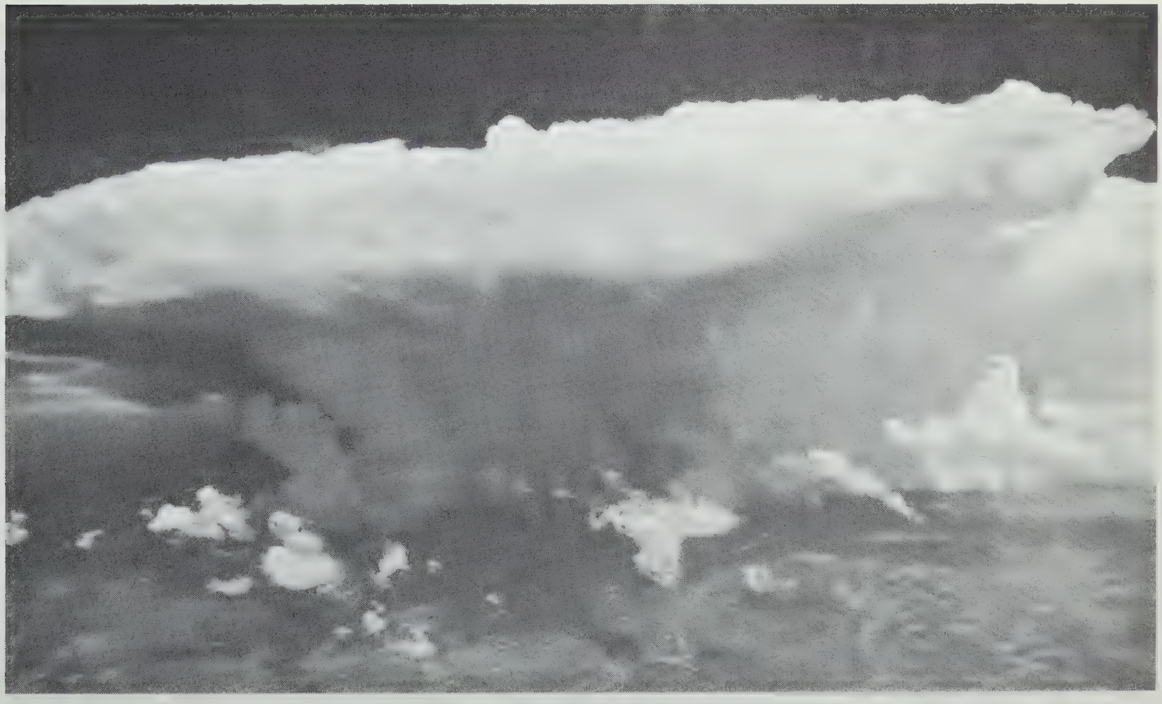
15-6 THUNDERSTORMS

The destructive hurricanes you read about in Chapter 14 are a special form of cyclone, or low-pressure storm. Fortunately, they are relatively rare over North America. The difference between a hurricane and a low-pressure storm is one of intensity. There are two other special forms of storms that differ from cyclones in their intensity and in the way they form.

The **thunderstorm** (see Figure 15-14) is the most common of the violent storms. It is a local atmospheric disturbance, rarely over a few miles in diameter. Thunderstorms usually travel only a relatively few miles before they end. There are several conditions that may produce thunderstorms. They may occur whenever two air masses with very different characteristics come in contact. Consequently a line of thunderstorms is often produced along a front.

Conditions within a single air mass will often produce an isolated thunderstorm. What are these conditions? First and

Figure 15-14 The clouds associated with this thunderstorm rise to 50,000 feet. Great violence is created in the clouds by the updrafts of air.



foremost, there must be unstable air. Second, there must be enough water vapor in the air to produce the precipitation and latent heat of condensation necessary for the storm.

The unstable condition may be brought about by many factors. Very often it is due to the local heating of the air close to the ground. Less often, cold air overtaking a mass of warm air causes the instability. A third cause is the forcing of the air to rise rapidly over a mountain. In general, therefore, rapidly rising air creates the conditions for a thunderstorm to form.

Strong heating of the earth's surface is a major cause of thunderstorms. Often, summer storms are referred to as "heat thunderstorms." This is a poor name, since these storms are not different from storms formed by other causes. July and August, when the air is hot and humid, are the most common months for thunderstorms. Insolation is converted to heat and radiated back into the atmosphere. The air warms, expands, and rises.

As shown in Figure 15-15, air moves in from the surrounding areas to replace the rising air. These are the strong, gusty winds that often precede a thunderstorm. The air flowing into the center of the forming storm is often saturated with

Figure 15-15 The life of a thunderstorm can be described in three stages. In the first stage there are updrafts throughout. The second stage is characterized by strong updrafts and downdrafts. When the storm is breaking up, the third stage, the wind is in the form of downdrafts.

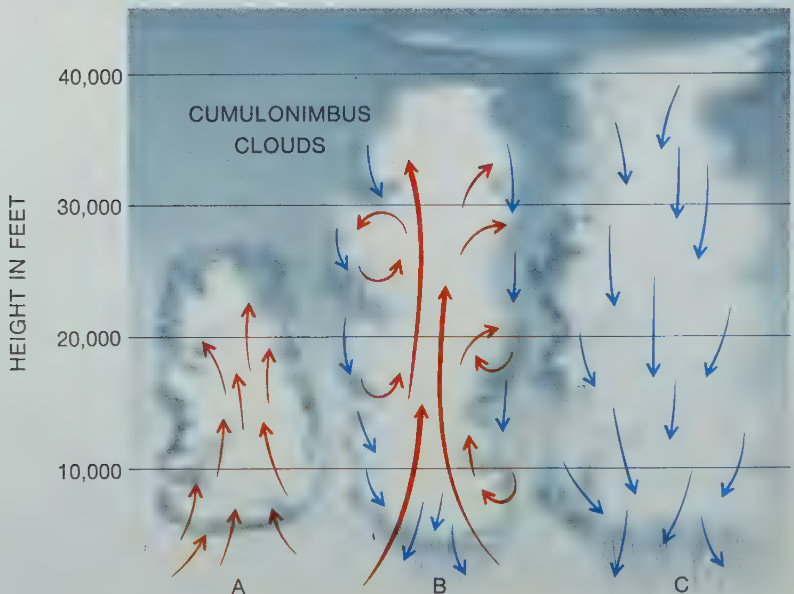


Figure 15-16 Cumulonimbus clouds, or thunderheads, are also called thunderstorm breeders. Thunderheads can be solitary clouds or a wall of many clouds, which looks like a range of mountains. One of the distinguishing features of a thunderhead is the characteristic anvil top.

water vapor. The column of hot, moist air rises thousands of feet with great speed. This rapid rise—a result of the highly unstable conditions—produces adiabatic cooling.

The water vapor of the expanding column of heated air condenses into huge **cumulonimbus** clouds (see Figure 15-16), often called *thunderheads*. As you watch, you can often see these growing. More cumulonimbus clouds form as the rising air column climbs higher into the cool, upper air. Cumulonimbus clouds may be as high as 65,000 feet. The flat base of the clouds represents the altitude at which condensation is occurring. Flyers always try to avoid thunderstorms because of the violent vertical air currents.

A thunderstorm is actually composed of independent, vertically moving "cells" of air, as shown in Figure 15-17. Within the updrafts, raindrops grow until they become so large (about 4 millimeters in diameter) that they can no longer hold together. As they fall in a downdraft, the drops break apart.

The process of convection produces vertically moving cells of air. Hence, a thunerstorm is a convective storm.

By a process still not well understood, different parts of a cumulonimbus cloud develop opposite electrical charges. When the charges grow to a critical size, a discharge, in the

Figure 15-18 Nature's fireworks in the form of lightning accompany storms associated with cumulonimbus clouds. Lightning can occur within the cloud or between the cloud and the earth.

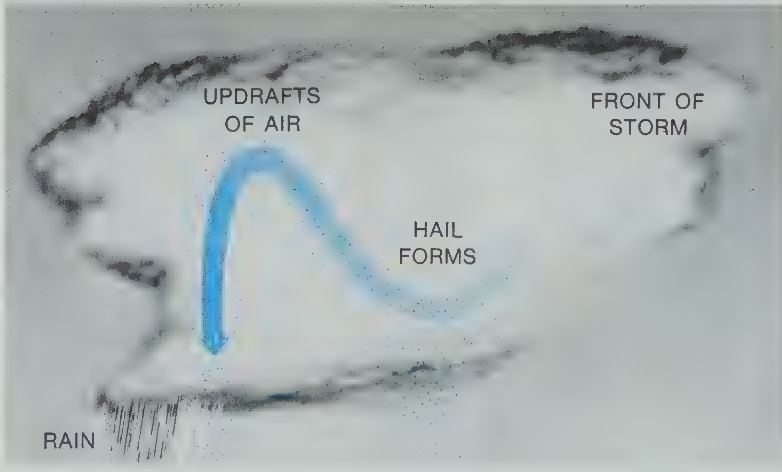


Figure 15-17 The vertically moving cells of air in a thunderstorm move water droplets up and down within the clouds. Rain or hailstones are the result of this alternate warming and cooling.

form of a giant spark, takes place between the oppositely charged areas. This is **lightning**. Sometimes the accumulation of opposite charges between the bottom of the cloud and the earth is great enough to cause a discharge between the cloud and the earth. Most lightning, however, takes place within the cloud (see Figure 15-18).

A bolt of lightning releases about 4×10^8 calories of heat energy in a few microseconds (one microsecond is one millionth of a second). Some of the energy is converted to light. This is the flash that we see. Most of the energy is released as heat. The heat is absorbed by the air, which expands immediately. The air is cooled and contracts rapidly when the heat is absorbed by the water in the clouds. The series of rapid expansions and contractions of the air along the path of the lightning bolt causes the surrounding air to vibrate. This vibration we hear as **thunder**.

Even in summer, hail is often associated with thunderstorms. The strong updrafts in the center of the storm carry raindrops upward. If they go high enough, they will freeze and begin to fall. As they fall into warmer air, they add a new layer of water. If another updraft captures them, the new layer of water will freeze and repeat the process. The growing hailstones gain new layers of ice each time they are lifted (see Figure 15-19). If they are tossed to high altitudes many times, hailstones the size of baseballs may be formed.

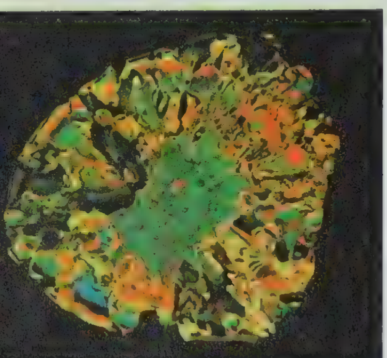


Figure 15-19 Hailstones, a series of concentric ice layers, are formed only in cumulonimbus clouds. This is a cross section of a hailstone photographed with polarized light.

A slightly different kind of thunderstorm from the ones described above is the **line storm**, shown in Figure 15-20. Line storms form along the fronts of a summer *mT* air mass that meets a weak *cP* or *mP* air mass. As the hot, humid *mT* air rises over the polar air, a line of thunderheads may form along the front. Although the cause is different, line storms behave just like thunderstorms.

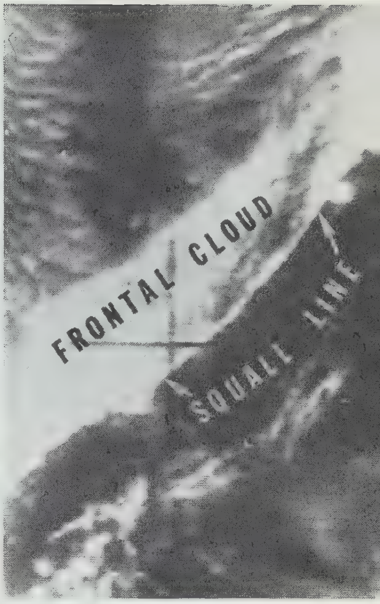


Figure 15-20 A line storm showing the meeting of the warm and cold fronts

15-7 TORNADOES

Conditions similar to those that result in line storms may sometimes result in a **tornado**, shown in Figure 15-21. These are the most spectacular of the local cyclones, and are often called *cyclones* or *twisters*. Although tornadoes may occur in any month, they are most common from late spring to early autumn. Then, the *mT* air in the Mississippi Valley may meet a still-powerful polar air mass.

The method of formation of a tornado is similar to that of a thunderstorm. The result, however, is a cyclone even more intense and with a much smaller diameter than a hurricane. Most tornadoes are about 600 feet wide. The path of a tornado may range to over 100 miles.

The winds in these small, tight storms reach extremely high velocities. The rising air may move over 100 miles per hour, and the horizontal winds blowing into the twister may reach 300 miles per hour. The tornado moves along its path as fast as 40 miles per hour, and usually passes over any one

Figure 15-21 When moist, warm maritime tropical air meets cold continental polar air, the result is a violent turning motion that can result in a tornado. Tornadoes occur in the United States mainly in the plains states.

Figure 15-22 Destruction caused by a tornado can be very erratic. Sometimes the buildings on one side of a street will be destroyed, while those on the other side will be relatively unharmed.

spot in about 30 seconds. The actual speed of the revolving winds cannot be measured but must be estimated. Speeds of 120 miles per hour have been recorded before the anemometer blew away. Winds moving at this speed would not account for destruction caused by a tornado.

The destructiveness of a tornado, which contains only 1/1,000 of the energy of a thunderstorm, comes from two factors: (1) All the energy is concentrated in a small-diameter storm. (2) The rapidly rising air in the funnel creates such a sudden drop in pressure that as the tornado passes over a building, the air rushes out of the building with explosive violence. Some results of a tornado's passage are shown in Figure 15-22.

Study Guide

1. What causes air to become unstable?
2. Why does hail often accompany a thunderstorm, even in summer?
3. Why are thunderstorms usually accompanied by high, gusty winds?
4. What causes lightning?
5. Why are tornadoes so destructive?

SUMMARY

Lows and highs follow each other across the country in irregular patterns under the influence of the prevailing westerlies. To look for these patterns, meteorologists plot on maps the information collected by weather stations. From past records, they try to fore-

cast the movements of the air masses and their fronts.

Meteorologists try to predict when air will become stable or unstable. Unstable air rises and may produce clouds and rain. Special forms of storms are the thunderstorm and the tornado.

REVIEW AND DISCUSSION QUESTIONS

1. A beach in summer is often the breeding ground for a thunderstorm. Explain why.
2. If warm air is less dense than cold air, how does a warm front develop?
3. How can a stable air mass become unstable?
4. On the beach on a hot summer day, a strong breeze usually blows in from over the water. At night, the wind reverses itself and usually blows out to sea from the land. Discuss the reasons for the formation of these land and sea breezes.
5. How does a meteorologist know where to place the warm and cold fronts when he draws a weather map?
6. Almost all the United States is in the belt of the prevailing westerlies. Why doesn't the wind always blow from the southwest in these areas?
7. Air moving eastward from the Pacific Ocean must pass over several mountain ranges before it reaches the East Coast. In all cases, a town on the western slopes of the mountains will have a higher annual rainfall than a town on the eastern slopes of the mountains. Explain why.
8. A common practice followed by people who are living in the path of an approaching tornado is to leave some of the windows in their houses open. How will this help to cut down on the damage?
9. Crystals of a chemical called silver iodide are shaped something like crystals of ice. Silver iodide is the chemical often used to "seed" clouds and make rain. Why do meteorologists think that silver iodide will help?
10. As a low preceded by a warm front and then a high preceded by a cold front pass the area where you live, describe the changes that will take place in the (a) temperature, (b) air pressure, (c) wind direction, (d) wind velocity, and (e) cloud and precipitation conditions.
11. Why does the warming of air over the land tend to cause unstable air?
12. Transatlantic flyers will take two courses depending on the kind of front that may be in their path. If it is a cold front, they will take a northern route. If it is a warm front, they will take a southern route. Flyers will not fly along the front. What are the reasons that influence the pilot's decision?

CHAPTER 16

WATER ON THE LAND

Rain or snow that has reached the surface of the earth ultimately returns to the atmosphere as water vapor. If rain falls on a surface that does not readily absorb water, such as concrete or rock, the water flows over the surface to become puddles or streams. If it falls on porous materials, most of the water is absorbed and slowly seeps underground. The effect of water flowing on the surface is different from the effect of water that has been absorbed.

16-1 RAIN ON BARE ROCK

Today only a small part of the earth's surface is exposed bedrock. Although we think of rock as being impervious to water, it is not. Many kinds of rocks, especially sedimentary, can absorb large quantities of water. Most igneous and metamorphic rocks, however, have very few open spaces between their mineral grains and therefore can absorb very little water.

The most widespread effect of rain on bare rock is the washing away of any small fragments that have been broken loose by weathering. These particles may be washed into depressions on the surface, where they become the beginnings of new soil. Any water absorbed by the rock speeds up the process of weathering.

In any one rainstorm not much change appears on rock surfaces. Very little material is removed. However, over long periods of time, the little bit done by each rainstorm accounts for the removal of much rock. We must always bear in mind that geologic processes occur very slowly, and a thousand years in the history of the earth is a very short time.

16-2 RAIN AND THE SOIL

Rain that falls on the soil may soak into it, run over its surface, or both. The fate of the water depends on the nature of

The Salinas River at Monterey Bay, California, deposits its sediments and discolors the ocean water.

the soil and the slope of the land. If the soil is porous and dry, it can absorb a large amount of water. If all the tiny openings between the soil particles are already filled or if the soil is mostly clay, most of the water will run off. Figure 16-1 shows how the character of the ground affects the absorption of water.

Groundwater is the name given to water located beneath the earth's surface. Some groundwater travels only a short distance before it is picked up by the roots of plants. Plants absorb water most actively during their growing season. Most of the water that is absorbed by plants is returned to the atmosphere as water vapor.

Heat energy must be used to evaporate the water released by plants. Such energy comes from the surfaces of leaves and from the air. Therefore, a forested area is usually cooler than a region that is covered only by grasses or that lacks vegetation.

The groundwater that is not picked up by plants settles through the soil until it reaches an impervious layer. Such a layer may be bedrock or a hard, compact layer of soil such as clay. The groundwater moves slowly downhill on the impervious layer.

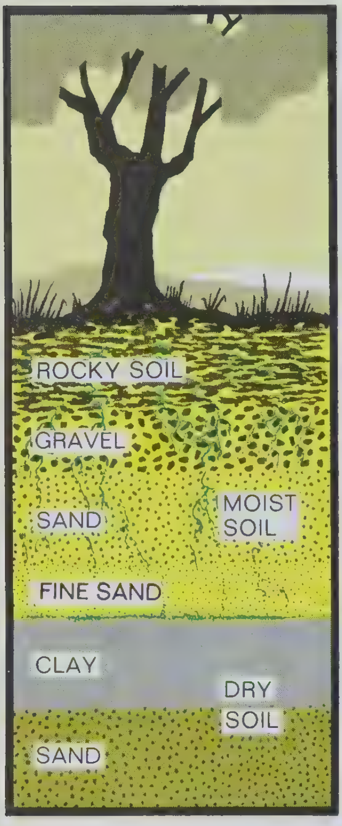


Figure 16-1 In soil, the ratio of the space between the particles to the mass of the particles, or porosity, is determined by the size of the particles. For example, sand particles are relatively large; therefore, sandy soil is very porous.

16-3 THE WORK OF GROUNDWATER

Groundwater moving through soil or porous rock is distributed in such thin layers or tiny drops that it is greatly slowed by friction. It may take weeks, months, or years for it to move a few miles. This means that groundwater uses its energy very slowly. As a result, it does not have the power to move large amounts of material.

The speed with which groundwater moves downslope depends on the size and shape of, and the amount of space between, the particles through which it is moving. Coarse gravel with large spaces between the pieces will allow the water to move with relative rapidity. Clay has such small spaces that it allows very little water to move through it and often acts as an impervious surface. Where there is clayey soil, there is usually poor drainage.

The movement of groundwater is very evident when you watch a spring. Here, groundwater flows to the surface. **Springs** occur where an impervious layer, such as clay or compact rock, meets the land surface. The groundwater that flows along this layer has filled the pores in the soil that rests on the impervious layer.

The top of the water-soaked layer of soil underground is called the **water table**. Below the water table the soil is always saturated with water. Rainwater moving downward through the soil may raise the level of the water table. During long dry spells, the water table sinks lower because of the natural drainage of the groundwater and human use. Figure 16-2 shows the relationship of the water table to the surface.

Water creeps upward in small spaces by a process called *capillary attraction.*

The soil above the water table may be moist. Water from the water table creeps upward a short way into this soil. You know that if you dip the corner of a blotter into water or ink, the liquid will be soaked up into the blotter. Many desert plants survive because of this process.

Much of the space between soil particles above the water table is filled with air. Soil geologists call this the **aerated zone**. The roots of some plants, such as alfalfa and willow, often grow through the aerated zone to reach the water table.

We have already learned that springs occur where the water table meets the surface. If the intersection of the ground and the water table occurs over a large area, a swamp or lake is formed. Some streams start from such areas.

Study Guide

1. Heat is needed to evaporate water. Where does this heat come from in a forest?
2. In many areas, about 50 percent of the rainfall is immediately returned to the atmosphere as water vapor. What plant functions are responsible for part of this return?
3. What factors determine whether water will penetrate the soil?
4. Draw a diagram to show how a spring may be formed.
5. What is a water table?

Figure 16-2 This cross section of a water table shows what might happen if the surface of the land became depressed. One of the results might be a small lake. What might be some other effects of this action?

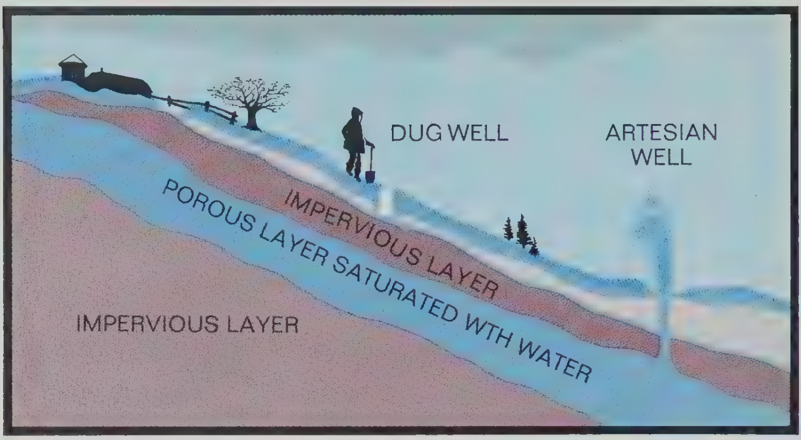


Figure 16-3 In a region of sloping strata, water pressure builds up in the aquifer. If a hole is drilled into the aquifer, the water will spurt out to a height dependent on the elevation of the source of the water above the aquifer.

16-4 AQUIFERS AND WELLS

aquifer (AK wuh fur); Latin; *aqua*, water + *ferre*, to bear.

artesian (ahr TEE zhun); from the province of Artois, France, where this type of well is abundant.

The layer of soil, rock, or alluvium through which groundwater flows is called an **aquifer**. This is a general name applied to any water-bearing layer. Occasionally, an aquifer occurs between two layers of impervious material such as shale or clay. The water trapped between the two impervious layers cannot escape unless the impervious rock ends or is broken. A formation like this is shown in Figure 16-3. An **artesian well** is one in which water rises above the level of the aquifer to the ground surface through a break in the impervious layer. This occurs when there is a great deal of water pressure in the aquifer.

In areas where there are no aquifers under sufficient pressure to force the water to the surface, the water must be pumped up. Wells are dug or drilled to a few feet below the water table. These wells tap the groundwater that is flowing closest to the surface. If the level of the water table drops, the well may run dry.

16-5 WATER IN LIMESTONE REGIONS

Water affects the land in limestone regions in a unique way. The major reason for this is that limestone is soluble in rainwater. As rain falls through the atmosphere, it dissolves

carbon dioxide. The two combine chemically to form a weak acid called carbonic acid. On the ground, the weak acid reacts with the solid calcium carbonate (limestone) to form a new compound, calcium bicarbonate. Calcium bicarbonate is soluble in water and is carried away by the moving groundwater (see Section 9-6).

Water may enter the rock through cracks, called **joints**, at the surface. It widens these joints by dissolving the limestone. In many limestone regions, there are no surface streams. All the water that reaches the surface finds its way underground through the joints. The underground water dissolves the calcium carbonate to form **solution tunnels** (see Figure 16-4).

As the groundwater penetrates deeper into the limestone below ground, the old solution tunnels are emptied. Eventually these may form a system of tunnels called **caves** or **caverns.** Water may be seen dripping from joints in the ceilings of the caverns.

As this water falls in drops and evaporates, the carbon dioxide is released back into the air. There is no longer a weak acid present to keep the calcium bicarbonate in solution. The solution breaks up, and the calcium carbonate is deposited again as solid limestone. This kind of limestone is called **travertine.** Chemically, it is the same as limestone. It is a rock made of the mineral calcite.

Figure 16-4 The water entering the earth through joints will dissolve the underlying limestone and form a solution tunnel.

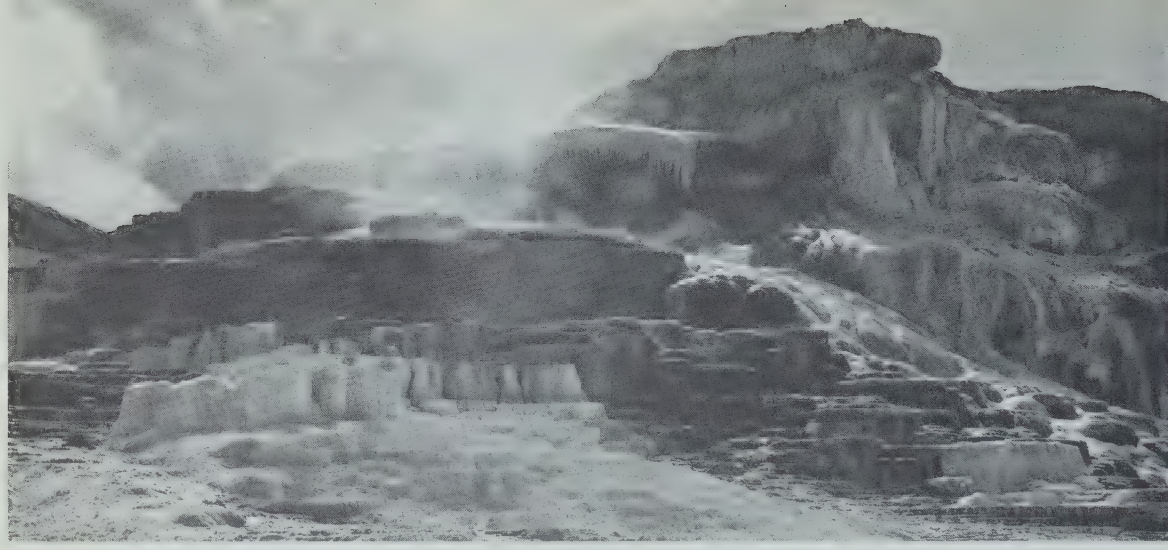


Figure 16-5 Calcium carbonate deposited from solution in surface waters forms travertine terraces such as these at Mammoth Hot Springs, Yellowstone National Park, Wyoming.

The travertine deposited by groundwater takes many forms. In areas where groundwater flows to the surface, travertine is deposited in layers. **Travertine terraces,** such as those shown in Figure 16-5, are beautifully colored by impurities that the groundwater has picked up. These terraces are frequently associated with springs in limestone areas.

stalactite (stuh LAK tyet); Greek: *stalaktos*, dripping.

stalagmite (stuh LAG myet); Greek: *stalagmos*, dropping.

As groundwater drips from the ceiling of a cave, travertine is deposited very slowly. These deposits hang like icicles from the ceiling and are called **stalactites**. If any of the water falls to the floor of the cave, other deposits of travertine form there. They grow up from the floor, like upside-down icicles, and are called **stalagmites.** The interior of a cave is shown in Figure 16-6.

Figure 16-6 Carlsbad Caverns National Park, New Mexico, is famous for its limestone formations. If a stalagmite grows upward far enough to meet the stalactite growing down above it, the two will meet and form a column of travertine.

Sometimes in a limestone region so much rock is dissolved along joints that deep pits are formed, called **sinkholes.** They vary in size from a few feet to many yards across. Occasionally the roof of a solution tunnel near the surface becomes so thin that the remaining rock can no longer support what is above it. The roof of the tunnel collapses and forms a long depression, called a **collapse valley** (see Figure 16-7). A region where the solution of limestone by groundwater has shaped the landscape is called a **karst** region.

Karst is the name of a limestone region in Yugoslavia where there are numerous sinkholes and underground streams.

As karst regions age, their appearance changes. At first there are many sinkholes. These may enlarge and join one another. Some collapse valleys may appear. When most of the limestone has been removed, the work of the water is almost finished. Streams appear in the lowlands, where they flow on nonlimestone formations. Between the streams, steep-sided low hills of limestone are all that is left of the original formations. Different stages in the development of karst typography can be seen near Mammoth Cave in Kentucky.

Study Guide

1. Explain the difference between an artesian well and a well that requires a pump.
2. What determines whether a particular type of rock will make a good aquifer?
3. Why do large caves form only in limestone regions?
4. How do sinkholes form?

Figure 16-7 The immense reflector for the radio-radar telescope of the Arecibo Ionospheric Observatory was constructed in one of the many sink-holes. Originally this area was flat. What happened to it?

16-6 STREAMS DRAIN THE LAND

Because the land is never perfectly level, water will always flow from one point to another on the surface. Any water moving across the surface of the land in a channel is called a **stream**, regardless of its size. The terms *river*, *stream*, *brook*, and *creek* are common names for streams of different sizes.

Streams usually unite with other streams to form larger ones. All the streams that unite and eventually reach the ocean as a major river are part of a **stream system**. The land from which a stream or stream system collects water is called its **watershed**. A watershed may be part of one mountain, or it may be millions of square miles of land. The watersheds of two neighboring stream systems are separated by a **divide**, which is a highland (see Figure 16-8).

Water must always flow downhill. In doing so, it has the power to erode the land. A stream system usually starts as a small mountain brook. It gradually widens as it is joined by other streams along its course until it becomes large enough to be considered a major river. The beginnings of a river are its **source**, or **headwaters**. The end of a river, where it emp-

Figure 16-8 The major stream systems in the United States. Each consists of several smaller systems that join and form a major stream system. The greatest of these is the Mississippi River system. As you can see, its watershed occupies about half the United States. On the way to the Gulf of Mexico it is joined by tributaries that drain part of the Appalachian Mountains and part of the Rocky Mountains.

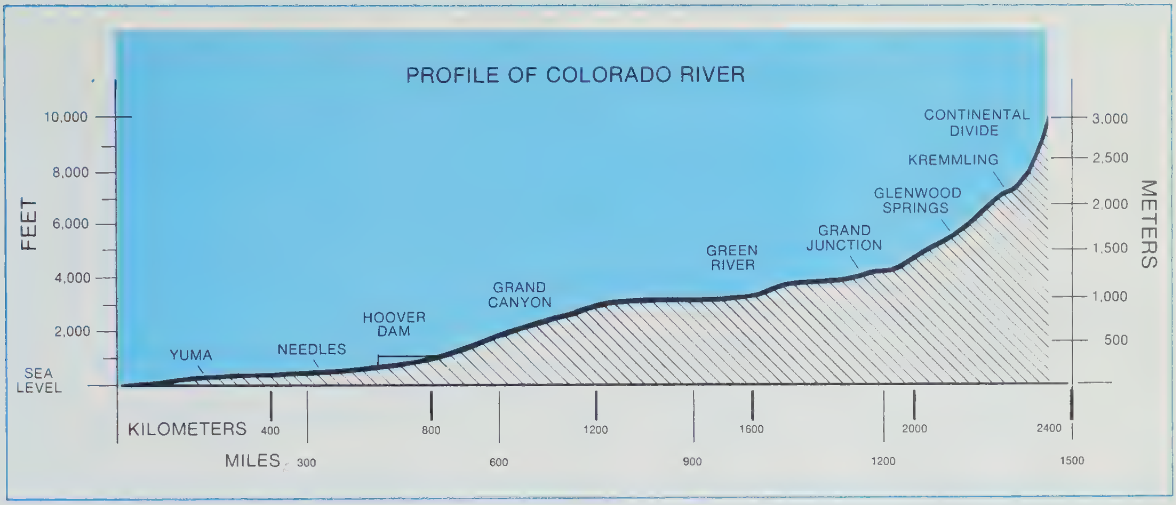


Figure 16-9 Profile of the Colorado River. If the Colorado River is 2,400 kilometers long and drops 3,000 meters to sea level, what is its average gradient? Why are there flat areas and steep areas?

ties into a large body of still water, such as an ocean, is called the **mouth**. The source is always higher than the mouth. Why?

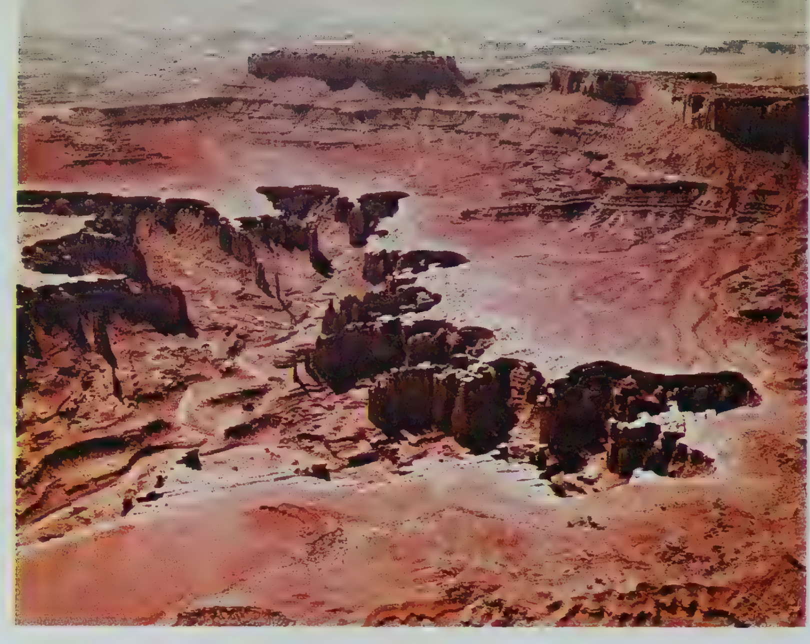
16-7 THE SLOPE OF STREAMS

The steepest parts of a stream system are generally near the headwaters. The least steep parts are near the mouth. As a stream erodes its bed, the slope of the land over which the stream flows becomes less steep. If nothing were to interfere, erosion would eventually reduce the slope of a stream until it was almost level. Water would then flow slowly all over the land. That minimum slope is called **base level**.

No major stream system ever completely reaches base level. Geologic changes, such as uplift of land, prevent this. The lower part of the Mississippi River system and the last few miles of the Colorado River system are almost at base level.

The steepness of a stream's course is determined by how much change in elevation above sea level occurs per unit of distance. This measurement is called the **stream gradient**. A stream with a high gradient flows over steep ground and may drop 100 feet in a mile. A slow-moving, almost level stream may drop less than 1 foot in a mile. The gradient of any stream changes throughout its length. Figure 16-9 shows the gradient and profile of a river. It should be obvious to you that a stream with a high gradient will generally flow faster than one with a low gradient. The faster a stream flows, the more work each pound of water can do.

Figure 16-10 A deeply eroded area in Utah shows the effect of headward erosion. Notice how the land is eroded uphill from the flow of the stream.



16-8 GROWTH OF A STREAM

A stream system begins when water starts to run off a high area in a definite path, or gully. Many gullies are formed on bare land during a rainstorm. If water follows a particular gully for any length of time, erosion deepens it into a **channel.**

An increased flow of water causes a gully to extend in a direction opposite to the flow of water. Although the water flows downhill, erosion extends the gully uphill. Figure 16-10 shows the results of this process, which is called **headward erosion.** As headward erosion continues, the stream channels collect water from a larger and larger area.

Study Guide

1. What is a stream gradient? How does it affect the erosive power of a stream?
2. List some of the major divides in the United States. What river systems do they separate?
3. Why are the Rocky Mountains called the Great Divide?
4. Explain how headward erosion can form a stream channel.

16-9 WINDING STREAMS

No natural stream flows in a straight line for a long distance. In mountainous areas it may wind around among hills. Boul-

ders, landslides, and fallen trees get in the way of a stream. Small streams cannot sweep such obstructions out of their way. Instead, the streams must swing around the obstacles.

When the stream gradient is low, slight obstructions will change the path of the stream. Instead of flowing in a straight line, the path becomes a series of S curves. These are called **meanders** (see Figure 16-11).

Meanders occur only in those streams that have a **floodplain**. This is the area of level land on either side of a river. It is the land over which a stream once flowed. The meandering channel of a river is cut into the alluvium of the floodplain.

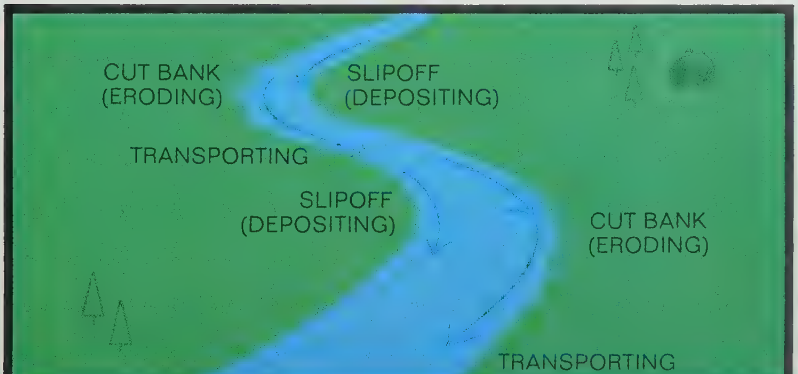
A meandering stream attacks one of its banks and then the other. As water flows against one bank, it erodes material and forms a **cutbank**. Directly across the river from the cutbank, the stream deposits some of its load and forms a **slipoff**. The actions of eroding and depositing at opposite banks of the stream, diagramed in Figure 16-12, are the major feature of meanders. The opposing actions are caused by differences in the velocity of the water at opposite sides of the stream.

Why should the two sides of a stream flow at different velocities while rounding the curve of a meander? This can be answered by using a familiar example. How do the members of a school band stay in a straight line when making a right turn on a football field? They do this by maintaining identical *angular velocities* but changing their *linear velocities*. Look back to Section 12-13 for an explanation of what is meant by angular velocity.

meander (mee AN dur); from the Maeander River in western Asia Minor, which was proverbial for its twisting course. The river is now called the Menderes.

Figure 16-11 This example of a meandering stream in its floodplain is found in Wyoming. How do you know that this stream has eroded its bed?

Figure 16-12 The erosion of the riverbank takes place at the cutbank, while the deposition of material such as sand and stones takes place at the slipoff.



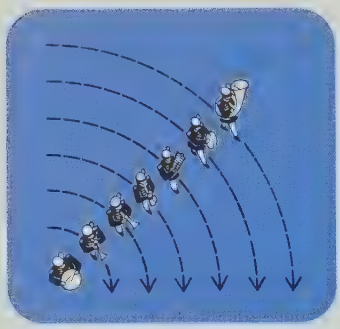


Figure 16-13 Angular velocity and linear velocity

The innermost musician in Figure 16-13 turns through 90 degrees while standing in place. This 90-degree turn is performed in the same time it takes the outermost musician to move through 90 degrees. The angular velocities of the two band members are the same. The linear velocities are different. The outermost musician covers much more ground than the one who just turns in place. Which one moves faster?

The same thing happens to water passing along a meander. The increased velocity of the water at the outer edge of the stream (see Figure 16-12) increases its kinetic energy. This gives the water a greater ability to erode its bank and to transport a load. At the inner part of the turn, the water slows down. It loses kinetic energy and therefore must deposit some of its load. However, the average velocity of the whole stream changes very little.

Meanders do not stay in the same place forever. They move downstream very slowly. If you compared the meanders in a river shown on a map made some years ago with an up-to-date map showing the same section of the river, you would see how far the meanders have traveled.

16-10 FLOODS IN OLD STREAMS

As surely as spring follows winter, low-gradient streams will flood. When the snow in the headwater region melts, the new water will increase the volume of the stream. If it does not flow between high banks, the stream will probably overflow and spread over the surrounding land. The picture at the beginning of this chapter shows a flooding river.

The floodwater may cut across meanders. This tends to shorten the stream's length without changing the elevation that the stream has dropped. In other words, the stream's gradient is increased. The increased gradient will increase the velocity, and therefore the eroding power, of the flooding stream.

When the water recedes, the river does not always return to its old channel. It may follow a new path across meanders. The water flowing in the new channel, or **cutoff**, may deposit enough alluvium at the ends of the meander to seal it. The meander is now an isolated body of water shaped like an old-fashioned oxbow. Such lakes are, therefore, called **oxbow lakes.** The formation of cutoffs and oxbows is shown in Figure 16-14.

In time, a stream may cut deeply into the alluvium of its bed. Then even the most severe floods will rarely rise high

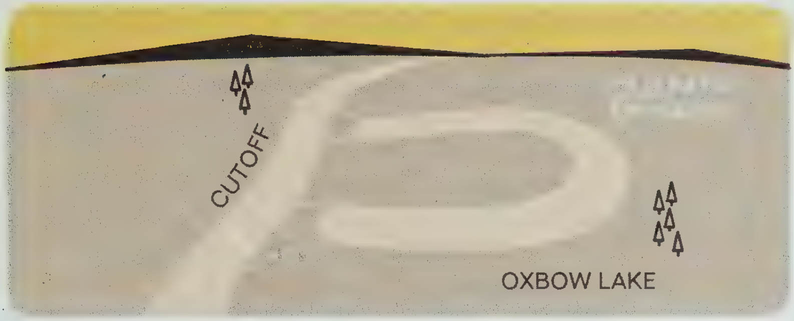


Figure 16-14 When the water in the stream is high during a flood, the stream may form a new channel, cutting off the old meander which then becomes an isolated, curved lake.

enough to reach the floodplain. On the old floodplain, now called a **river terrace**, are slight, curving irregularities that are the scars of old meanders (see Figure 16-16). In parts of some river systems, there may be several river terraces, one above the other. The river terraces are the record of the river's work as it swings back and forth across the valley floor it occupies.

16-11 THE MOUTH OF A RIVER

Where a river flows into an ocean or a lake, its speed decreases until it almost stops. This may occur at the mouth of the river or many miles offshore.

For instance, when the sediment-loaded fresh water of the Mississippi reaches the Gulf of Mexico, it slows down. The coarser and larger particles settle to the bottom first. Then the smaller, lighter particles settle out. This results in the formation of distinct layers of sediments on the sea bottom.

Figure 16-15 A meandering stream in Canada that shows a great amount of movement. Find an oxbow lake, a scar of an old meander, and a series of terraces.

Figure 16-16 The Nile delta from an altitude of 100 miles, taken on the Gemini IV flight. Deltas are formed by progressive deposition, damming, and rerouting of distributary streams. Notice the necks of land at the mouth of each distributary.

Figure 16-17 The Mississippi delta does not have the shape of the Greek letter Δ. It is more like a bird's foot, with distributaries forming the claws.

For many miles beyond the mouth of the Amazon River, the ocean water is quite fresh. The Amazon discharges so much fresh water into the Atlantic that it forms a layer that floats on the ocean water. Why should fresh water float on salty water?

The influence of Mississippi River water extends only a short distance into the Gulf of Mexico. There are two major reasons for this difference. The Mississippi discharges much less water into the ocean than the Amazon does. The Amazon ends in one huge mouth several miles across. The Mississippi has not one but many small mouths along 70 miles of coastline. For these reasons and others, the Mississippi River ends in a large, muddy alluvial deposit called a **delta.**

The name *delta* was first used about 2,000 years ago by Greek geographers. It comes from the Greek letter *delta*, written Δ. If you look at the aerial view of the delta of the Nile River in Figure 16-16, you can guess why the name was chosen.

The Mississippi delta is called a **bird's-foot delta**. As you can see in Figure 16-17, the delta is crossed by several branches of the main river. On a delta, these branches are called **distributaries**.

Most river deltas are not so large or obvious as the Mississippi delta. Some rivers have no deltas. They do not flow directly into the oceans, but into a drowned river valley that connects with the sea. Such formations are called **estuaries**. These are interesting places to study because of the gradual change from marine life to freshwater life. The Hudson River in New York ends in an estuary and has no delta. Look at a map of this area and try to explain the reason for the lack of a delta. The great Amazon River transports a large amount of sediment, but it has an estuary rather than a delta.

All the features of streams and groundwater described in this chapter involve energy. How is all the work of streams accomplished? The water that falls as rain or snow and produces a stream retains some of the solar energy that originally lifted it into the atmosphere. In the next chapter we will discuss how a stream spends this energy.

Study Guide

1. Explain why meanders move slowly along a stream valley.
2. How do oxbow lakes develop?
3. Why doesn't fresh water entering an ocean immediately become salty?
4. Why does a delta form?

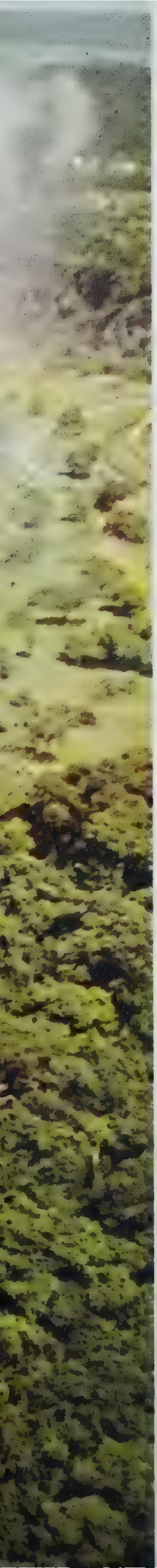
SUMMARY

Several things may happen to water that falls on the land. It may evaporate back into the air, flow on the surface as streams, or travel underground as groundwater. Groundwater generally moves very slowly because of much friction with soil particles. A water-bearing zone beneath the surface is called an aquifer. Man has learned to tap these to obtain water. Groundwater will form caves and other formations in areas composed of limestone. Water mixed with carbon dioxide can dissolve limestone and redeposit it as travertine.

All streams have certain characteristics in common. They always flow from a high area toward a base level, which is usually the elevation of the point where they empty into the sea. Along the way, they erode and change the land over which they flow. Meanders, or curving paths, are common in most large streams. A river sometimes ends in a delta, a large deposit of alluvium at its mouth.

REVIEW AND DISCUSSION QUESTIONS

1. What happens to a river that does not flow into the ocean?
2. How do river terraces give clues to the life history of a river?
3. Once an oxbow lake has formed, what is the source of its water?
4. If the boundary between two countries were a river, why might disputes arise about the location of the boundary?
5. What precautions should be taken when disposing of wastes in an area where water is obtained from wells?
6. In southern Idaho there are extensive lava flows north of the Snake River. They cover thousands of square miles and have a cap of solid rock. Many springs enter the river on the north side. They come from beds of volcanic ash that occur between the layers of lava. Explain how this situation developed.
7. In what areas of the country would limestone not be a good material to use for buildings? Why?
8. The St. Lawrence River, in the northeastern United States, almost never overflows. Use a map of the area to explain why.
9. Why can a stream never completely erode to base level the land over which it flows?
10. Spring water is very rarely pure water. Why?
11. In 1910 a small pond was built by damming a small stream in a prairie grasslands. The pond was about 4 feet deep and covered about an acre of land. Today there is only a grassy meadow where the pond was. What has happened?
12. Why does the Amazon River not have a delta?



CHAPTER 17

THE ENERGY OF STREAMS

Earth scientists use the word *stream* in several ways. In meteorology it means a relatively narrow mass of air moving more rapidly than the adjacent air. The jet stream is an example. Oceanographers use the word for such features as the Gulf Stream. This is a narrow body of water that flows more rapidly than the water surrounding it.

You have already learned that geologists use the word *stream* for water flowing in a channel across the land. Streams of air and water have several things in common. Most important, they are fluids, and their kinetic energy enables them to do work.

17-1 STREAM FLOW

Streams of water on the land do three kinds of work as they flow through channels. They erode material from their beds, they transport this material, and they deposit it. All parts of streams transport material. Some parts of streams do more eroding than depositing, whereas other parts do the reverse. The energy for the work of streams comes from the potential energy of position. That form of energy is converted to kinetic energy by the movement of the flowing water.

The downslope movement of every stream is the result of the force of gravity. Gravity speeds up, or accelerates, the movement of the flowing water. Slow and sluggish rivers may travel downslope at a third of a mile per hour. Rushing mountain streams may travel as fast as 25 miles per hour. How fast the stream flows and how much water is flowing determine how much energy is available to do work.

If nothing interfered with the flow of a stream—that is, if there were no friction—streams would flow at very high velocities. Let us see just how fast this would be for an ordinary stream with a gradient of 5 feet per mile after flowing for 1 hour. To solve this problem, we need to use some formulas developed by physicists.

Victoria Falls of Zambia and Rhodesia, Africa, show the power of water.

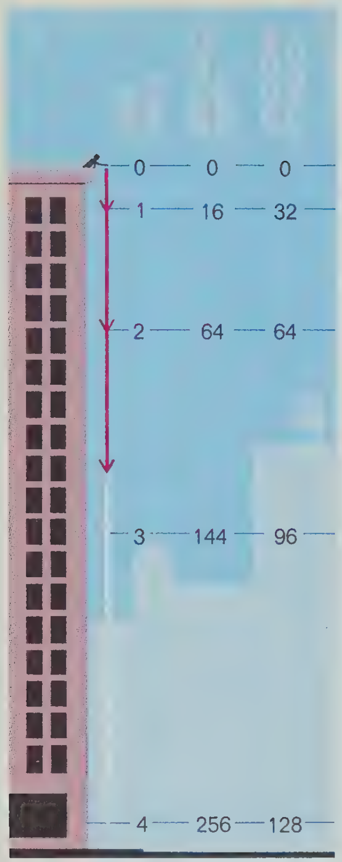


Figure 17-1 Acceleration of a free-falling object. If the fall were to last one second longer than shown, how far would the object fall?

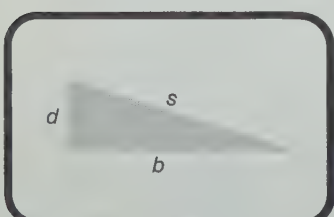


Figure 17-2 The hypotenuse of the triangle represents the slope.

Consider this situation. If you hold a ball in your hand and then drop it, it will fall to the ground under the influence of gravity (see Figure 17-1). The longer the ball falls, the faster it will fall. (We are neglecting the friction between the ball and the air through which it falls.) Gravity is continuously pulling the ball toward the center of the earth.

When the ball is falling freely, the effect of gravity is at its maximum. Under these conditions the ball will increase its velocity 32 feet per second each second it falls. This increase in velocity is the ball's acceleration. (For a review of this concept, see Section 2-3.) The effect of gravity on the acceleration of a falling body is called g, and its value in the English system is 32 feet per second per second, which is written 32 feet/sec^2.

Likewise, a stream of water moving down a slope is subject to the pull of gravity. However, the water does not fall freely; it slips down the slope. This reduces the acceleration from g to a much slower rate. We will call that slower rate of acceleration *a*. The rate *a* is the result of the slope's effect on g.

Now look at Figure 17-2. The hypotenuse, *s*, of this triangle represents the slope down which the water flows. The base, *b*, is the horizontal distance the water moves. The line *d* is the vertical distance the water drops. The effect of the slope on the acceleration of the water can be calculated by the following equation.

$$\text{acceleration} = \text{gravity}\ \frac{\text{vertical distance}}{\text{hypotenuse}}$$

We do not know the distance *s*. However, with a gentle gradient, such as 5 feet per mile (5,280 feet), the distances *s* and *b* will be so similar that we can substitute one for the other. For very steep slopes we would somehow have to measure *s*. Now let us substitute the numbers we have in the equation.

$$a = g\frac{d}{s}$$

$$a = \frac{32\ \text{ft}}{\text{sec}^2} \times \frac{5\ \text{ft}}{5{,}280\ \text{ft}}$$

$$a = \frac{0.03\ \text{ft}}{\text{sec}^2}$$

This means that water standing perfectly still at the top of the slope will be flowing down the slope at the rate of 0.03

feet per second at the end of the first second. At the end of the second second, it will be moving 0.06 feet per second (0.03×2). At the end of the first minute (60 seconds), it will be flowing at the rate of 0.03×60, or 1.80 feet per second. At the end of an hour (60 minutes), its velocity will be 1.80×60, or 108 feet per second, or 74 miles per hour! No stream ever flows that rapidly.

A stream like the one we have taken for an example usually flows at about 3 miles per hour. What has slowed it down to such a snail's pace from its theoretical speed of 74 miles per hour? The answer is friction. This friction can be divided into two kinds: friction within the stream of water, and friction between the water and its channel.

Study Guide

1. Name three kinds of work done by streams.
2. How can the slope down which a stream flows be used to calculate the acceleration of the water?
3. Why does a stream always flow more slowly than its theoretical maximum speed?
4. Convert 3 miles per hour to meters per minute.

17-2 KINDS OF FLOW

If you look at a stream flowing through a very smooth channel, you will notice several things. First, you will notice that the stream's surface is quite smooth, especially near the middle. You will also notice that twigs or leaves floating on the water near the edges of the stream are moving less rapidly than those in the middle.

If you look very closely at the flow along the edge of the stream, you will see that the water swirls in little eddies. The flow in the central part of the stream is different from the flow at the edges near the banks. We call the smooth, central flow **laminar flow**. At the edges of the stream, where there are eddies, we call the flow **turbulent flow** (see Figure 17-3).

laminar (LAM uh nur). Arranged in thin layers.

turbulent (TUR byuh lunt); Latin: *turbulentus*, stormy.

Laminar flow occurs with a minimum of friction between layers of water moving at slightly different rates. In turbulent flow there is much more friction.

The energy used to create turbulence leaves less kinetic energy to move the water downstream. Because less energy is available, the turbulent water flows more slowly than the parts of the stream with laminar flow.

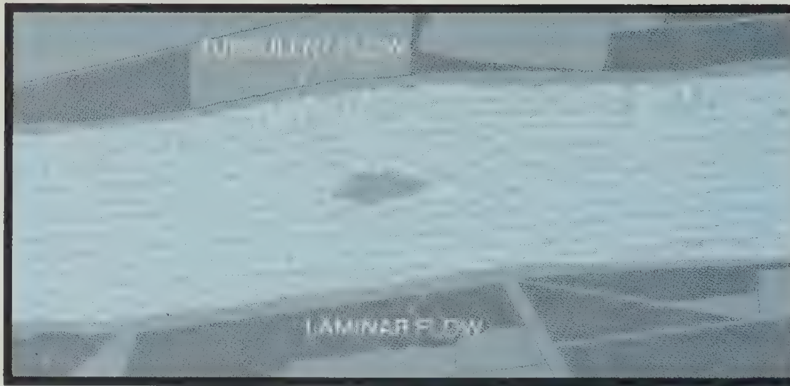


Figure 17-3 The varying velocities of the water in the stream are shown by the length of the arrows. The turbulent flow along the irregular bank represents more friction than does the faster-moving, laminar flow.

Figure 17-4 Boulders and other debris in a stream slow down the flow of water. What kind of flow would you expect to find around a boulder?

17-3 THE CAUSES OF TURBULENT FLOW

If you observe a mountain stream that has many boulders in its channel, you will not see areas of laminar flow. The entire stream is composed of turbulently flowing water. Each time the flowing water meets an obstruction, the water must move aside. This interrupts the smooth flow and causes eddies.

Recall that eddies are observed near the edges in a laminar stream. These eddies of turbulent water are caused by friction between the water and the bed and banks of the stream. Observations of many natural streams indicate that even the quietest of them exhibit some turbulent flow. Most small streams show no laminar flow at all.

Much of a stream's kinetic energy is used to overcome obstructions in its path. Kinetic energy also lifts the water at the bottom of the stream over the uneven surface of the stream bed. What happens to the remaining kinetic energy?

17-4 THE STREAM AND ITS LOAD

The material a stream carries along with it is called its **load**. Streams carry loads in several different ways. Part of the load is carried suspended in the moving water. Materials that dissolve in water are said to be carried in solution. The rest of the load is dragged or rolled along the bottom. The amount of load that can be carried depends on the remaining kinetic energy. The amount of available energy is in turn related to the dimensions and shape of the cross section of the stream.

Consider two streams with the same cross-sectional area, flowing down identical slopes. Their load-carrying ability depends on the dimensions of the beds that are in contact with the streams. This area is called the **wetted perimeter**.

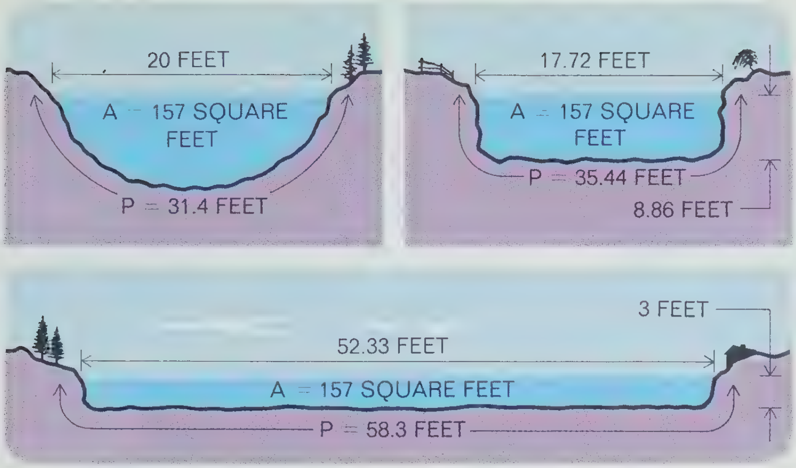


Figure 17-5 Even though each cross section of the diagramatic streams has the same area, each possesses a different amount of available energy. Why?

Look at Figure 17-5, showing three stream cross sections. *A* is the area, and *p* is the wetted perimeter. In each case, the area of the cross section is the same. The stream shape having the smallest wetted perimeter is a semicircle. A stream with a cross section closely approaching a semicircle will have the maximum amount of energy available to erode and to transport its load. A shallow, broad stream will have the least available energy.

A stream's load is either in solution, in suspension, or rolled along the stream bed (see Section 5-2). Grains of sand or pebbles that are being rolled along the bed sometimes strike an obstruction and bounce up into the water. There they are carried with it for a short distance. More frequently, fine sand or silt is scooped up by a vertical eddy and carried up into the water. These particles remain suspended in the water for a short time.

Figure 17-6 Clay particles in water suspension illustrate the colloidal state. What is the appearance of this condition?

Clay particles are usually carried in suspension. Most often, they are composed of small clusters of clay molecules that are loosely attached to surrounding water molecules (see Figure 17-6). This condition is called the **colloidal state**. Colloidal particles are only slightly denser than water, so they settle very slowly. The mass of such particles is so small compared to the area of their surfaces that friction with the water prevents them from settling very rapidly.

colloidal (kuh LOYD ul).

The size of the particles that can be moved along the bed of a stream depends on the velocity of the stream. It also depends on whether there is enough water in the stream to completely cover the particles.

A stream moving less than 7 inches per second (about 0.45 miles per hour) cannot erode its bed and can carry only the finest colloidal material. Table 17–1 shows the diameters of the largest particles that can be moved by streams flowing at various velocities.

Table 17–1 Particle size and stream velocity

Material	Maximum diameter	Minimum stream velocity feet/sec	mph	cm/sec
Fine clay	0.0004 inch (0.001 mm)	0.656	0.45	18
Fine sand	0.008 inch (0.02 mm)	0.656	0.45	18
Coarse sand	0.08 inch (2.0 mm)	1.15	0.78	35
Small pebbles	0.25 inch (10.0 mm)	2.3	1.57	70
Large pebbles	2.5 inches (100.0 mm)	9.0	6.15	260
Small boulders	19.7 inches (500.0 mm)	19.0	12.92	580
Large boulders	39.4 inches (1000 mm)	26.2	17.85	800

Study Guide

1. From your observations, how does the flow of a stream vary at any one place? What terms do earth scientists use to describe these effects?
2. How do different kinds of flow affect the work done by a stream?
3. What causes variations in stream flow?
4. What are the differences in the ways the two forms of flowing water use energy?
5. In what ways does a stream carry its load?
6. How fast does a stream have to flow to move coarse sand?

17-5 WHEN STREAMS FLOOD

Whenever the water in a stream rises above its average level, we say the stream is flooding. Sometimes, so much water flows in a stream channel that the channel cannot hold the water. Then the stream overflows its banks.

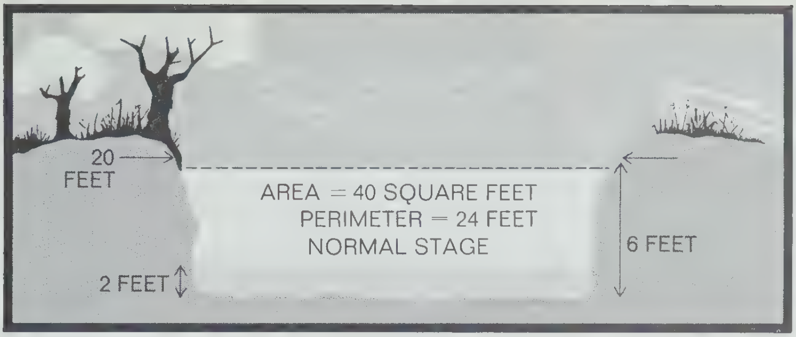


Figure 17-7 In this cross section showing the flooded state of a normal stream, the wetted perimeter does not increase in proportion to the area. This causes an increase in the velocity of the stream, which results in an increase of erosion by the stream.

The work done by the river is affected by flooding. When the floodwater is contained within the channel of the stream, there is usually a great increase in the area of its cross section. There is also a smaller increase in the wetted perimeter (see Figure 17-7). As a result, there is more energy available to the stream. The increase in energy tends to increase the velocity of the stream. Thus, much more work, or erosion, can be done on the bed of the stream during periods of flood than during periods of normal flow.

In mountainous country a sudden, heavy rainfall may cause a stream that is normally a few inches deep to swell to a torrent several feet deep. The steep gradient of mountain streams permits water to rush downhill at speeds greater than 20 miles per hour. The force and depth of the speeding water enables a stream to cover and move large boulders. Flooded mountain streams can do great damage. Highway engineers working in mountainous country try to place roads high enough above the streams so they will not be reached by floodwater.

Most large rivers flood in the spring, when snow that has piled up during the winter melts quickly during a spring rain (see Figure 17-8). The cross section of water over these flooded areas is very broad and shallow. Therefore, the wetted perimeter is great, thus slowing down the floodwaters. The velocity of the water is also reduced by the turbulence that develops as the water moves over the vegetation.

The slowing of the water greatly reduces its capacity to carry a load. Therefore, much material is deposited on the flooded land, and the floodplain is built up. The soil formed

Figure 17-8 Often, in the spring, water from melting snow and heavy rainfall causes rivers to flood. This river has increased in area and wetted perimeter. Which stream flows faster, the flooded or the unflooded?

in this way is rich in plant nutrients. River floodplains are some of the world's best agricultural land. The floodplain may extend for many miles on either side of a river's banks.

An interesting thing happens at the edge of the river channel when a river overflows. Usually, this is a place where there are thickets of willows and other plants that require much water. When the rising water reaches this area, it loses velocity very rapidly and drops much of its load among the stems of the plants. This load builds the shoulder of the river channel a little higher than it was. In time, a very definite ridge develops (see Figure 17-9). Such ridges are called **natural levees**.

levee (LEH vee); French: *lever*, to raise.

We make artificial levees to protect land on a floodplain from further flooding. Thousands of miles of man-made levees have been constructed along the Mississippi River to keep it within its banks during annual spring floods. Although such levees are costly, they prevent damage that is much more costly.

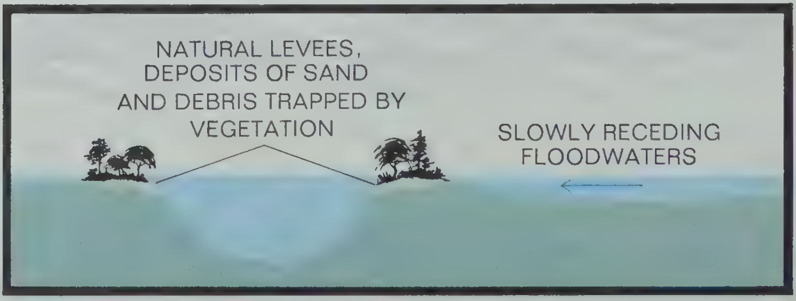


Figure 17-9 Plant life growing along a stream are the first obstacles to stop and hold the debris of the stream when it floods. Such material eventually forms a mound, or natural levee, along the stream.

Study Guide

1. How is the work of a stream affected if it remains within its channel during flood stage?
2. Why does a stream in flood have more erosive power if it does not overflow its banks?
3. What happens to the energy of a flooded stream as it overflows its banks?
4. Explain why a stream that is normally only a trickle of water can move heavy construction equipment at flood stage.
5. Why do people return to floodplains to live?
6. Explain the formation and importance of natural levees.

17-6 VARIATION IN THE CROSS SECTION OF A STREAM

If you were to stretch a string directly across a stream at any point, a certain amount of water would pass under the string in one second. This amount of water would depend on the velocity and the cross-sectional area of the stream.

Let us take two points on an imaginary stream and see how their cross sections affect the flow. The upstream point we will call *A*, and the downstream point, *B*. The cross section of the stream at point *A* is 4 square feet, and the velocity is 5 feet per second. At point *B* the velocity is 2 feet per second. What must be the cross section at point *B*? Figure 17-10 shows how to visualize this problem.

What volume of water passes point *A* in one second? The water doing so has a cross section of 4 square feet and a "length" of 5 feet. Therefore, 20 cubic feet of water must pass point *A* in one second.

This same amount of water must also pass point *B* in one second. Why? At point *B* the water is moving more slowly than at *A*—only 2 feet per second. What must be the cross section of the stream at point *B* to allow 20 cubic feet of water to pass in one second?

Now let us do a little thinking about the effect of the shape of the stream channel on the flow. We will assume the simplest situation—the materials of the stream bed at points *A* and *B* are the same. What is the relationship between stream velocity and the ability to erode? At which point will the stream be cutting into its bed at the faster rate? At which point is the stream likely to be deeper? Since the same amount of water must pass each point in one second, at which point, *A* or *B*, would you expect the stream to be wider?

Figure 17-10 The volume and velocity of water in an ideal stream

17-7 GRADIENT AND SEDIMENTATION

Figure 17-11 Dams of alluvium cause streams to form new channels and eventually to form an alluvial fan. Such an alluvial fan, in the Tasman Valley of New Zealand, is pictured here.

As the gradient changes, what happens to a stream's ability to carry a load? The faster a stream flows, the more material it can carry per unit volume, say, per cubic foot of water. What happens to the velocity of a stream when its gradient is reduced? What effect does this have on the material the stream is carrying?

If the change in gradient is a gradual one, the stream first drops the largest particles it is carrying. As the gradient is further reduced, the stream drops smaller and smaller particles. If the change in gradient is abrupt, a mixture of different-sized particles is dropped. Only those that the slower water can carry will be moved farther downstream. This sorting of sediment by streams was one of the things Hutton observed.

When a mountain stream moves onto more level land at the foot of the mountain, it drops most of its load at the point where the gradient changes abruptly. This action tends to dam the stream, which then must flow around the dam to get out of the mountain. Each time the stream changes its course a little, the abrupt change in gradient causes it to block its own path.

Soon the end of the mountain valley down which the stream flows becomes partly filled with alluvium. The stream then flows over the alluvium, and the action repeats itself. As a result, a low hill of alluvium, shaped like part of a cone, is built at the lower end of the valley and out onto the more level ground. This kind of deposit, shown in Figure 17-11, is called an **alluvial fan**. Often the stream that built the alluvial fan breaks into several smaller streams, called distributaries (see Section 16-11), as it flows down the slope of the fan. These streams are usually reunited to form a single stream once they are off the fan.

Study Guide

1. Describe what determines how much water passes a given point in a stream at any one time.
2. What changes could occur in a stream that would cause the velocity to vary?
3. If at point *A* on a stream the velocity is 6 feet per second and the cross section is 7 square feet, how much water will pass point *A* in one second?
4. At point *B* on the stream in question 4, the water's velocity is 3 feet per second. What is the cross section at this point?

5. Explain how sediments are sorted by a stream.
6. Where are alluvial fans most likely to be formed?

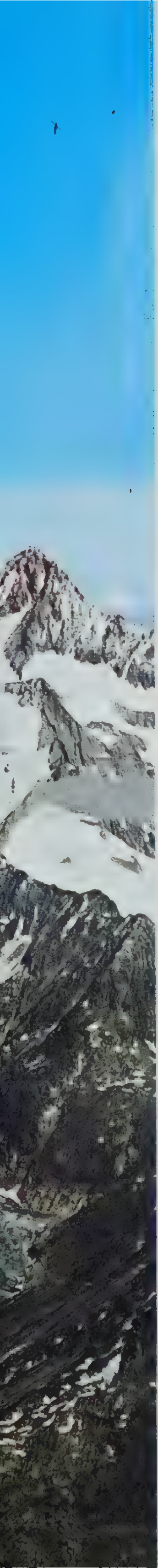
SUMMARY

The work done by streams can be divided into three kinds: erosion, transportation, and deposition. The energy for this work is the kinetic energy of the stream. Most of the kinetic energy of the stream is consumed in overcoming friction, eroding the stream channel, and transporting the load.

Very little of the energy is used to move the water downstream. Floodplains are formed when overflowing rivers decrease in speed and drop their loads. Variation in the velocity of the stream affects its cross section and determines whether it is eroding, or depositing its load.

REVIEW AND DISCUSSION QUESTIONS

1. Would flooding of the land last longer in a region composed of sandy soil or one with clay soil? Explain your answer.
2. Water empties from a tank into a ditch that has a gradient of 3 feet per mile. What is the theoretical maximum velocity that the water will reach after flowing for 15 minutes?
3. How long will it take a ball dropped from the roof of a 700-foot-high building to reach the ground, assuming there is no friction with the air?
4. Would natural levees be higher, or lower, after floodwaters receded? Explain your answer.
5. Are fossils likely to be more abundant in a delta or in an alluvial fan? Why?
6. Would an alluvial fan be likely to form if the area where a stream emerged from the mountains was heavily forested? Explain.
7. Explain why the Mississippi River has not cut a deep, narrow canyon as the Colorado River has.
8. Explain why clear water is less effective than muddy water in eroding the land.
9. Why do distributaries develop on deltas and alluvial fans?



CHAPTER **18**

VALLEY GLACIERS

Almost a hundred and fifty years ago, there was a boy in Switzerland who later became one of the great scientists of America. His name was Louis Agassiz. As a young man, Agassiz visited parts of Germany. There he saw boulders scattered across the fields and low hills in straight lines, or **boulder trains**. Most of the geologists of the day believed the boulders had dropped from melting icebergs that had floated over the land during the great flood in the time of Noah.

18-1 AGASSIZ AND GLACIATION

There were three things about these boulder trains that bothered Agassiz. First, although the stones were somewhat rounded, many appeared to have been scraped flat on one or more sides. On some he could see parallel scratches. Second, the boulders were arranged in distinct patterns across the fields. Third, he noticed that the rocks composing the boulder trains were of various kinds. In Switzerland he had seen boulder trains, in valleys whose upper ends were filled with the ice of glaciers.

Agassiz traveled widely in northern Europe. In many regions he observed features that he believed were related to glaciers. He noticed great grooves and scratches on bedrock, boulders that were scratched and flattened on one or more sides, and large deposits of unsorted debris, called **moraines**.

In 1846, Agassiz came to America. As soon as he was settled in Cambridge, Massachusetts, he began to explore New England, and later he went as far west as Lake Superior. Throughout the northern part of the United States, Agassiz found moraines, flat-sided boulders, boulder trains, and grooves in bedrock. Everywhere he traveled, he saw more and more evidence to support his theory that glaciers had covered the land. He was sure that a great ice sheet had existed in North America as well as in Europe.

High above this Alpine glacier is its area of perpetual snow.

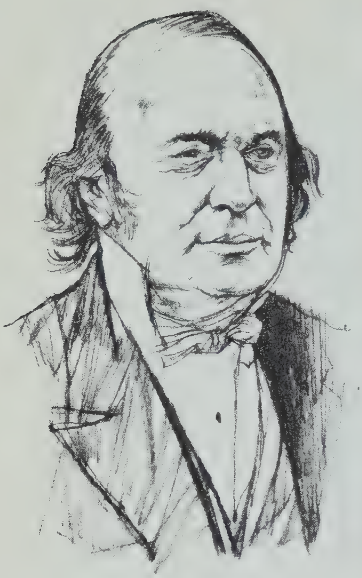


Figure 18-1 Louis Agassiz (AG uh see) (Swiss-American, 1807–1873). Agassiz's Swiss birth made him naturally interested in glaciers and glaciation. He studied the Ice Ages and the movements of glaciers in northern Europe. Agassiz came to the United States to lecture and was so interested in the evidence of glaciation that he stayed and became a professor of natural history at Harvard University.

Figure 18-2 The advance and retreat of a glacier can sometimes be traced by the boulder trains that are left behind. This boulder train is at Hogencamp Mountain, New York.

In America, Agassiz found that many geologists accepted his theory. As these men continued to explore the country, they gathered more evidence to support it. Today we believe Agassiz was right—great ice sheets once covered most of Canada and much of the northern half of the United States. Since 1948, scientists have used the carbon-14 method to date wood found buried in moraine. They have concluded that these great glaciers were active as recently as 12,000 years ago.

valley glaciers

18-2 GEOLOGISTS CONTINUE TO STUDY THE EVIDENCE LEFT BY GLACIERS

continental glaciers
ice sheets

Geologists have learned that there are two kinds of glaciers. Those that form in the mountains are called **valley glaciers**, and those that spread over great areas of land are called **continental glaciers** or **ice sheets**. The earth has been partially covered by continental ice sheets at least three times in its long history. Geologists still do not know exactly why glaciation occurs.

Since we cannot study glaciers in the laboratory, we have to go to the glaciers themselves. Until recently, it was difficult to live in Greenland or Antarctica, where the great ice caps are today. Geologists, therefore, studied the glaciers in the more accessible mountains. The glaciers of Switzerland were easy to explore because there were many villages nearby. Although geologists have studied glaciers on every continent, much of what we know about mountain glaciers was learned in the Alps of Switzerland. Within the last decade, studies of glacial phenomena have been made on the Antarctic ice sheet, where the photograph reproduced in Figure 18-3 was made.

18-3 SNOW REMAINS ON THE MOUNTAINS FOR A LONG TIME

Most mountains in Switzerland that are more than 13,000 feet high have glaciers clinging to their sides (see the photograph at the beginning of this chapter). Of course, not all mountains have glaciers. Whitehouse Mountain, in western Colorado, towers well above 13,000 feet, but there is no glacier upon it.

In early June, the top of Whitehouse Mountain is still heavily clothed with snow. In the valley at the base of the mountain it is warm, and the trees are fully in leaf. By the

Figure 18-3 Scientists from many countries have built research stations in Antarctica so that they can study glaciers. They also learn how Antarctica's weather conditions affect worldwide weather.

Figure 18-4 When snow falls and when it melts depend on altitude and latitude. An area such as the Colorado Rockies shows this relationship.

eskars
drumlins

end of August, all the snow from the previous winter has disappeared from the mountain. During the autumn months, rain falls at the base of the mountain, and snow falls on the mountain top. Snow falls earlier in the fall and lasts longer into the summer on the tops of high mountains than in the nearby lowlands (see Figure 18-4).

Why are there no glaciers on Whitehouse Mountain, whereas most Swiss mountains of the same height have at least one? Part of the answer may be that the snowfall in the Swiss mountains is greater. In earth science there is seldom a simple cause for a phenomenon. The amount of snowfall is only one factor in the formation of a glacier. Are the Rocky Mountains in Colorado warmed more by the sun than the Swiss Alps are? (Hint: The Colorado Rockies are closer to the equator than the Alps are.)

18-4 LOCATION IS A FACTOR IN GLACIER FORMATION

Where on a mountain will a glacier form? It will develop in the upper and colder part, of course. But we need a better answer than that. It will form on the part of the mountain

where the snow is deepest and where the sun's rays will melt away the least amount of snow during the year. Where does this happen on a mountain? The precipitation that falls on a mountain is brought to it by winds. In the middle latitudes of the Northern Hemisphere, the average wind blows from the southwest. As the wind rises along a mountain side, it cools and its water vapor condenses. It seems that most of the snow should be on the southwestern side of the mountains.

When the glaciers of the Rocky Mountains are examined, however, most of them are found on the northeastern flanks of the mountains. What is wrong with our theory? We have said that a glacier will form where there is the greatest accumulation of snow. We have also said that snowfall is greatest on the southwestern side of the mountains. The answer is that snowfall and snow accumulation are not the same thing. The southwestern side of the Rockies is also the windy side. Much of the snow that falls on the southwestern side is blown by the winds over the top of the mountains and accumulates on the northeastern side.

Another factor that controls the formation of glaciers is the amount of solar energy available to melt the accumulated snow. At any point in the Northern Hemisphere north of the Tropic of Cancer, the sun is always south of the zenith at noon. The southern face of mountains in the middle latitudes of the Northern Hemisphere will always receive more solar energy than the northern face. Snow will melt more rapidly on the southern side than on the northern side of these mountains.

When conditions are right, glaciers will form on any high mountain. In the Rocky Mountains, glaciers are found as far south as 38°N latitude. In Mexico, the summits of the giant volcanoes Popocatepetl and Ixtacihuatl, both more than 17,000 feet high, have glaciers on their flanks. There are even some glaciers near the equator, in the high mountains of Ecuador.

Study Guide

1. List three observations that led Agassiz to believe the land was once covered by glaciers.
2. Where were glaciers first studied? Why?
3. What is a boulder train?
4. How does altitude affect the growth of glaciers?
5. Explain the formation of glaciers near the equator.
6. Why do glaciers usually form on the northeastern side of mountains in the Northern Hemisphere?

18-5 HOW DO VALLEY GLACIERS FORM?

Glaciers are sometimes called "rivers of ice." Why compare a glacier to a river? A river flows in the valley it formed. It deepens or widens the valley by wearing away the valley floor and sides. The river transports debris eroded from the valley, and when the river slows down, this debris is deposited as alluvium.

Glaciers do all these things, too. They deepen and widen the valley in which they flow. They pick up and carry debris. Glaciers deposit their load when the ice melts. So we can accept valley glaciers as rivers of ice.

We know that glaciers will form on mountainsides where the annual snowfall is so great that the sun's heat cannot melt all the accumulated snow. Melting and refreezing changes the remaining snow from the fluffy flakes that have fallen to icy granules that tend to stick together. This partially compacted, granular snow is called **firn**. Skiers often call this *corn snow*.

As more snow accumulates each year, the firn underneath becomes more and more compressed. This changes its character. The pressure gets rid of the spaces between the granules. Firn becomes compressed into a solid mass, in which the remains of the granules can still be seen. This solid mass of granular ice is sometimes called **névé**. Further compression over the years changes the structure of the accumulated névé until it becomes the flowing ice of the glacier. The change from new-fallen snow at the surface of a glacier to firn, then to névé, and then to solid ice at the bottom is a gradual one. There are no distinct boundaries between the layers.

You will find that many of the words we use to describe glaciers come from the French language. Glaciers were first studied in Switzerland, where French is a native language. The word "glacier" comes from *glace*, the French word for ice.

18-6 HOW DOES THE ICE MOVE?

In the summer the sun's rays partially melt the mass of ice. Water trickles underneath and along the edges of the glacier. The glacier is frozen to the bedrock in many places. Therefore, it will stay on the side of the mountain as long as gravity does not overcome the friction between the glacier and the mountainside. A glacier does not move down a mountainside simply by sliding. Instead, it flows.

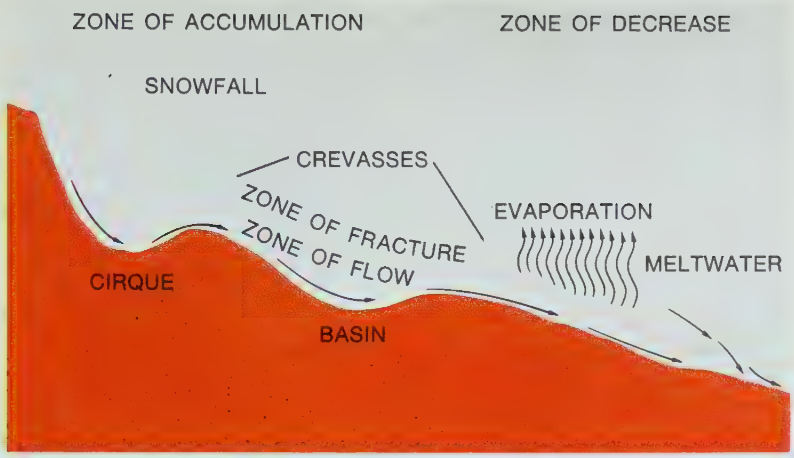


Figure 18-5 Pressure exerted by the weight of overlying ice causes the plastic zone of the glacier to flow more rapidly than its other parts.

You know that a piece of ice is brittle. If you hit it with a hammer, it shatters like glass because of the quick change in pressure upon it. The ice at the bottom of a glacier is under great constant pressure from the ice on top of it. This does not have the same effect as a quick change in pressure.

When a solid substance like ice or steel is subjected to constant pressure, it can flow like a fluid. The curved parts of automobiles, such as the fenders, are formed by pressing a sheet of heated steel under great pressure into a mold. While under pressure, the steel flows into the shape of a fender. Substances that flow when under pressure are called **plastic**. The weight of a column of ice 50 to 60 meters (150 to 200 feet) high is sufficient to make the ice beneath it plastic.

Pressure produced by the force of gravity causes the plastic ice deep in a glacier to flow. It flows slowly, from a few inches to a few feet each day. The rate of flow depends on many factors such as the steepness of the slope, the thickness of the ice, the roughness of the surface under the ice, and the temperature of the ice, and probably on several factors that we know nothing about at present.

We know that glaciers do not move downhill at a uniform rate. Geologists have shown that the bottom part of the glacier, which is in contact with the ground, moves more slowly than the ice above the bottom. This is because of the friction between the bottom of the ice and the mountainside. The brittle ice at the surface of the glacier is carried along by the plastic flow of the ice beneath it, as shown in Figure 18-5.

Whenever a glacier passes over uneven ground, cracks form in the upper part of the ice. These cracks, called **crevasses**, form because the bottom part of the ice is plastic.

crevasses (kruh VAS uz).

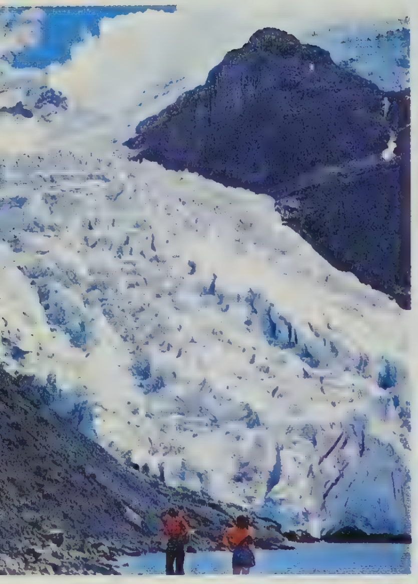


Figure 18-7 A large area of seracs on the glacier of Mount Robson, British Columbia

Figure 18-6 In order for the surface of a glacier to adjust to the flowing lower ice, the brittle top ice develops great cracks, often 100 feet deep. Crevasses often appear at sharp bends and steps in the valley.

while the top part is brittle. When the ice moves over an uneven portion of the bed, the top part cannot bend to the shape of the land, and it cracks (see Figure 18-6). At times, the crevasses intersect one another, producing huge blocks of ice that stand upright like pinnacles. This formation is called a **serac**. An area of seracs is seen in Figure 18-7.

serac (suh RAK).

18-7 BIRTHPLACE OF A GLACIER

During the day, glacial ice melts and fills the cracks in the bedrock with water. What happens to rocks when water has seeped into cracks and freezes there? The force applied to the rock by the expansion of the freezing water breaks the rock. If you camp near an active glacier in the summer, in the quiet of the night you may hear the booming noise caused by the breaking rock. The broken pieces of rock are frozen into the ice and become part of the glacier.

Figure 18-8 Notice where a former glacier has gouged out the side of the mountain, leaving a cirque and a U-shaped valley.

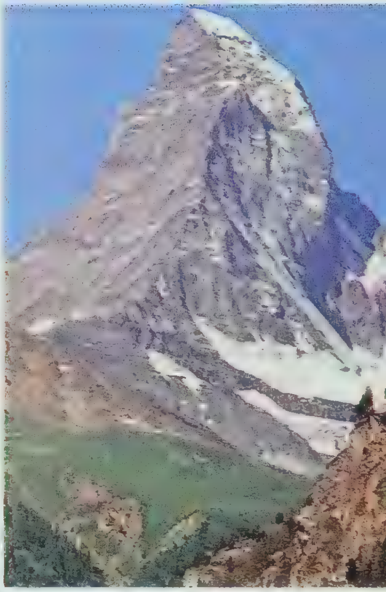


Figure 18-9 Scaling the Matterhorn has been a goal of mountain climbers for years. The steep faces of cirques and arêtes make any horn a challenge to climb.

After many years, a glacier will remove enough rock from the upper part of a mountain to make a depression shaped like a half-bowl. Where a glacier has disappeared, it looks as if someone with a giant ice-cream dipper has scooped out a piece of the mountain. The steep-walled basin in which a glacier originates is called a **cirque** (see Figure 18-8). Usually, more than one cirque will form on a mountain. High ridges are left between the cirques, where the ice has not eroded all the rock. These ridges are called **arêtes**. Mountain climbers will often follow these arêtes to reach the summit of a mountain.

cirque (surk).

arête (uh RAYT).

If several cirques and arètes form around the top of a mountain, the peak gets a very rugged, pointy appearance. Glaciated mountains such as these are called **horns**. The most famous of these is the Matterhorn, in Switzerland, shown in Figure 18-9. A small lake in a rock basin will sometimes be left in a vacated cirque. Such a lake is called a **tarn**, a Scottish name.

18-8 GLACIAL AND RIVER VALLEYS

Rivers flowing through mountain valleys are rarely as much as 10 feet deep. This means that do not extend far up the sides of their valleys. Where streams flow constantly, valleys slope uniformly from the crest of the mountain to the floor of the valley. This gives the valley a **V-shaped** cross section.

Valley glaciers are often a thousand or more feet thick. They extend far up the sides of the old stream valley through which they move. Where a glacier has worked upon a valley, the cross section is different. The ice has eroded much more material from the valley wall, and the cross section of the valley has changed from V-shaped to **U-shaped**. The two types of valleys are compared in Figure 18-10. A U-shaped glacial valley is called a **glacial trough**.

Almost every river is formed by several smaller, tributary streams that have joined together. The same is true of mountain glaciers. In the case of streams, the beds of the tributaries and of the main stream are always at the same height above sea level where they join. In valleys from which glaciers have disappeared, there are often U-shaped tributary valleys, entering from the side. Some tributary valleys are at the same level as the main valley where they join. Such a formation is shown in Figure 18-11.

In many cases, however, the floor of the valley of the tributary glacier enters the main glacial valley high up on its walls. Such valleys are called **hanging valleys** (see Figure 18-

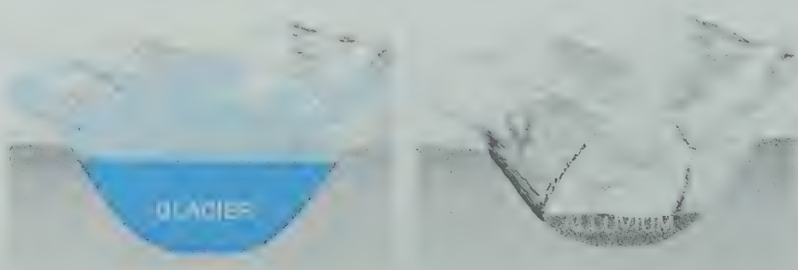


Figure 18-11 *(Left)* A valley filled with ice at the greatest period of glaciation. Notice the tributary glaciers entering at the sides of the main glacier. The lines on the surface of the glacier represent rock debris brought by the tributary glacier. *(Right)* The same valley after the glacier has melted. The former tributary glaciers have formed hanging valleys high above the main valley. Notice the lines of debris left by the glacier along the sides of the main valley. The valley has a thick layer of alluvium.

Figure 18-10 *(Upper)* U-shaped valleys are gouged out by glaciers. *(Lower)* V-shaped valleys are formed by rivers.

V shaped formed by rivers
U shaped formed by glaciers

Figure 18-12 The glacier moved from upper left to lower right. As it moved across the rock, it polished it, dug grooves in it, and plucked out broken fragments from it.

11). The two valleys are at different heights because of differences in the thickness of the ice in the glaciers that formed them. If the two glaciers that joined were of the same thickness, their valleys would meet at the same level. If they were of different thicknesses, a hanging valley would form.

Study Guide

1. What is névé?
2. What factors determine how fast a glacier will move?
3. How do crevasses form?
4. Explain why arêtes are often used by climbers to reach the peak of a mountain.
5. Why are glacial valleys usually U-shaped?
6. Under what conditions will a solid flow as if it were a liquid?

18-9 SCRATCHES AND GROOVES ON ROCKS

As a glacier moves down a valley, the stones that are frozen into the ice scratch and scrape the bedrock. Where the bedrock is soft, the glacier digs into it quite rapidly. Where the bedrock is hard, the glacier can only abrade and polish it. This abrasion leaves marks on the bedrock. When these marks are little more than scratches, they are called **striae**. Frequently, these are seen on the most compact rock that the glacier has passed over. Striae are also found on the flattened faces of the stones that had scratched the underlying bedrock.

In places where the bedrock is of just the right hardness, long, deep **grooves** are left behind. Good examples of glacial grooves are seen infrequently, usually only when the soil that covers them is removed. Striae and grooves, such as those in Figure 18-12, are some of the clues that geologists use to recognize an area that was once glaciated.

18-10 THE LIFE OF A GLACIER DEPENDS ON THE CLIMATE

Glaciers exist only as long as the climate is cold enough to produce at least as much ice as will melt in a year. On its downhill journey, a glacier arrives at a place where ice melts faster than it is produced or than it moves down from the area above. This is the end of the glacier and is called the **snout** (see Figure 18-13).

Mountain glaciers grow or decline in annual spurts. Meteorologists have learned that no two years have the same amount of precipitation or the same pattern of temperatures. In cold, wet years, glaciers grow rapidly and move farther downhill. What happens in warm, dry years is not so simple. If it is not warm enough to melt all the snow that falls during the winter, the glacier will grow a little. If all the new snow is melted, but none of the névé disappears, the glacier will "stand still." If it is warm and dry enough to melt some of the névé of previous years, the glacier will retreat.

The last time that climatic conditions were just right for the growth of new glaciers was from about A.D. 1000 to A.D. 1500. Since 1500 the climate has been getting warmer, but not uniformly. Warmer periods have been alternating with cooler periods. Now we are in one of the warmer periods and most glaciers are retreating.

Scientists have not yet discovered the reasons for these climatic changes. They do know that these changes have

Figure 18-13 A glacial snout is the lower end of a glacier. Some are as small as this one; others are hundreds of feet wide.

been on a smaller scale than the changes that caused millions of square miles of the continents to be covered by ice between 15,000 and 20,000 years ago.

18-11 A GLACIER DROPS ITS LOAD

On its downhill journey, the snout of a glacier will arrive at a place where it wastes away. Under the influence of the sun's rays, more ice melts than is moved down from higher up on the mountainside. There the debris that has been frozen into the glacier will be deposited as the ice melts.

We have learned that streams transport and deposit their loads. As a stream begins to slow down, it drops its heaviest particles first and its lightest particles last. In this way it sorts out its load. A glacier, however, behaves differently. Because of the way a glacier carries its load, particles are not sorted when the ice melts. Thus, the particles that a glacier drops at its snout are made up of everything from finely ground-up rock, called **rock flour**, to huge boulders, called **erratics**.

If you came upon a mass of debris in a valley, how could you tell whether it is stream or glacial deposit? The stream-transported materials would be sorted by size and weight and would be deposited in layers. The glacial material would probably be a jumbled pile of debris and would range from rock flour to erratics.

Another difference could be seen in the material in the valley. The pieces of debris left by a stream would be smoothly rounded in most cases. This, of course, is because of the tumbling action of the water. In contrast, the fragments left by the glacier were held in one position for a long time. Therefore, the surface that was dragged over the bedrock is worn quite smooth. During the journey of the ice, these fragments occasionally get caught, tear loose from the ice, turn a little, and then become refrozen in it. This exposes another side to be worn flat. Many stones left by melting glaciers have worn, flattened sides, called **facets** (see Figure 18-14).

Figure 18-14 These smooth, faceted stones, containing striae, were once frozen into a glacier.

We have already learned that piles of loose material dropped by a glacier are called moraines. Moraines are named by the position they had in the glacier. Debris that is piled up at the snout of a glacier is called **terminal moraine** or **end moraine**. The debris left along the sides of the ice is called **lateral moraine**. The debris dropped from the bottom of the ice along the ground is called **ground moraine**. Material carried in the middle of a glacier that was formed by joining tributaries is called **medial moraine**. The number of

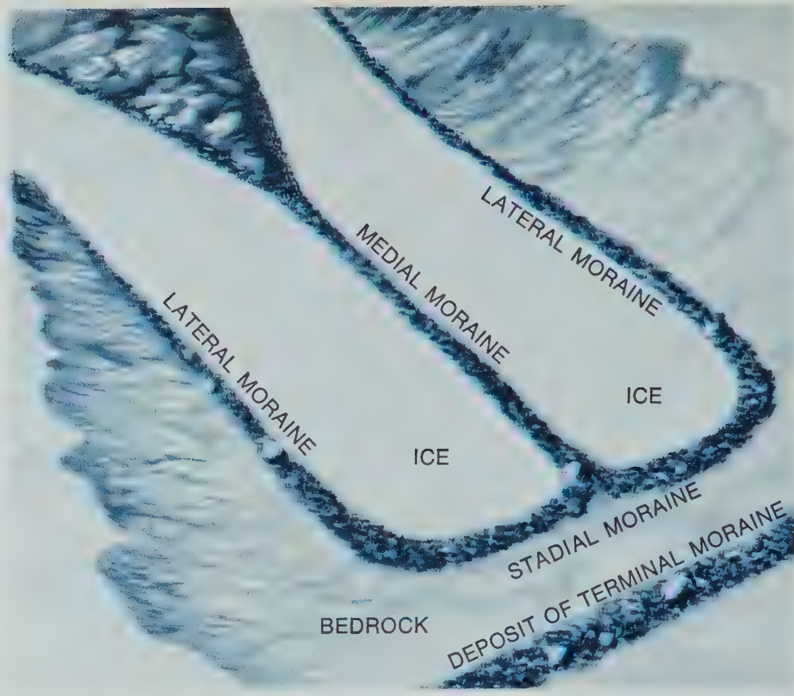


Figure 18-15 All types of moraine are made of rock debris formed by the action of glaciers. The type of moraine depends upon where the rock debris was deposited by the glacier.

medial moraines is an indication of the number of tributary glaciers that joined to form the main valley glacier. Figure 18-15 shows the various types of moraine.

Figure 18-16 Weathering and glacial action have produced this talus slope at the foot of the mountain. Notice the tarn in the foreground.

18-12 WHAT HAPPENS AFTER THE ICE RETREATS?

While a glacier is growing, the ice presses against the cirque and valley walls. When the glacier has disappeared, there is no longer anything to hold the rock walls in place except the strength of the rock itself. Much of the rock in the upper part of the valley is cracked and broken from frost action.

After the ice has gone, the frost-broken stones from these steep walls fall into the valley. In some places, millions of tons have fallen, forming great piles of debris called **talus slopes**. Talus slopes, like the one in Figure 18-16, may form anywhere rock is broken by weathering. Sometimes they are large enough to extend far out into and some distance down the valley. They are then called **rock glaciers**.

If a glacial trough is formed in an area of soft rock, the ice may erode a basin, which becomes a lake when the ice melts. Other lakes may form in a different manner. Ice and moraine

in a glacial trough may dam the mouth of a tributary valley. The water in the tributary valley will then accumulate behind the dam and form a glacial lake.

Some of these lakes are temporary and last only as long as the ice that forms the dam does not melt. Others will remain behind great dams of moraine long after the ice has melted. In time the lake may drain by cutting through the moraine dam. This may be speeded up by water from the lake filtering through the coarse debris of the moraine, thus helping to remove the finer materials.

Material of glacial origin that is carried away from the melting ice by streams is called **fluvioglacial outwash**. This kind of alluvium is somewhat sorted by stream action yet contains pebbles and boulders shaped by the glaciers.

As the glacier melts, alluvium is deposited in the glacial trough. Slowly, the bottom of the trough changes from a U shape to a broad, flat floor of alluvium. The streams that flow down the valley cut channels into the alluvium, transporting sediments to the rivers that will ultimately carry them to the ocean.

18-13 GLACIERS ON A COAST

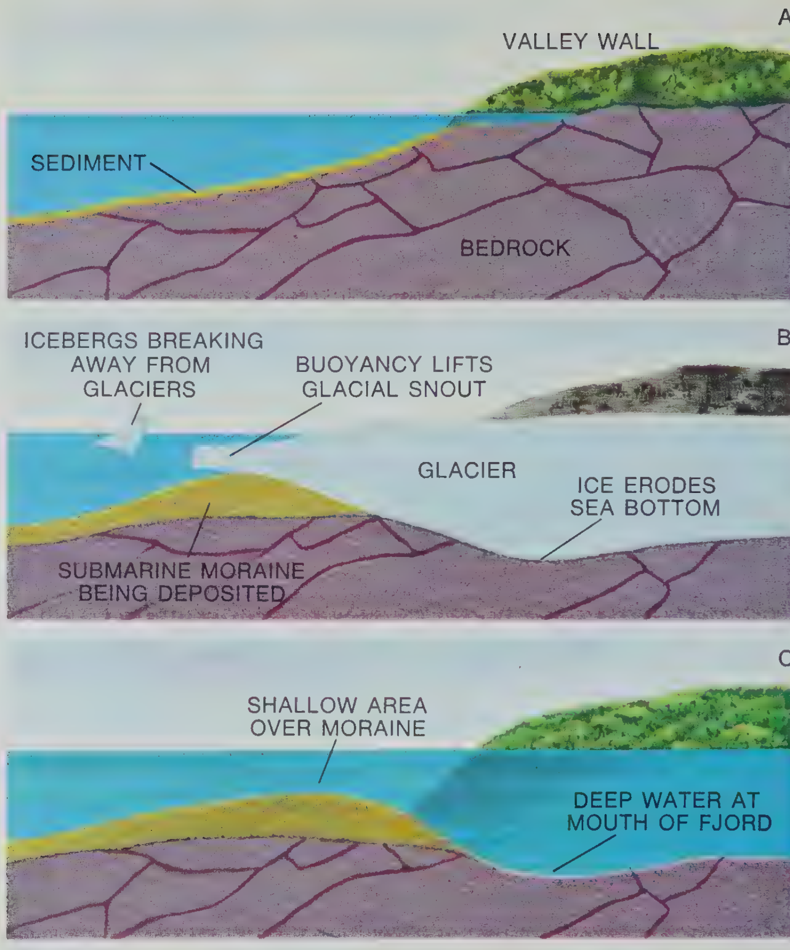
In high latitudes some mountain glaciers descend to sea level and even push out into the ocean. So long as the ice is much thicker than the water is deep, the glacier deepens its trough underwater. As the glacier pushes into deeper and deeper water, buoyancy of the ice raises the snout off the bottom. If the buoyancy becomes great enough, huge blocks of ice break off from the snout and become icebergs.

The debris that is carried in the ice is dropped to the floor of the ocean as the ice melts. This produces an underwater moraine, as shown in Figure 18-17. When a glacier that has entered the ocean melts, its trough is flooded by the sea. A long, narrow, steep-walled bay may be formed where the glacial trough was eroded below the level of the ocean. Such a flooded valley is called a **fjord**, the Norwegian name for it. In the United States there are many fine examples of fjords in Alaska.

fjord (fee AWRD).

The water in a fjord is often much deeper than it is in the ocean just outside the fjord. Buoyancy of the ice in the seawater counteracts the weight of the ice. Thus, it does not erode the glacial trough as effectively in deep water as it does where there is little or no buoyancy. Another factor that makes the water shallow offshore is the morainal material

Figure 18-17 (A) Mouth of stream before glaciation. (B) Glacier meets the ocean at the mouth of the stream. (C) A fjord remains after the glacier has retreated and left a deep channel with a shallow entrance, or sill.



that is piled up on the sea bottom. Figure 18-17 diagrams the long section of a fjord before and after the ice has left it.

Study Guide

1. What is the difference between glacial striae and glacial grooves?
2. What is an erratic?
3. Explain why glacially transported stones are usually flattened on at least one side.
4. Explain how a fjord is formed.
5. Is it possible for a glacier to stand still? How?
6. What is a moraine?

SUMMARY

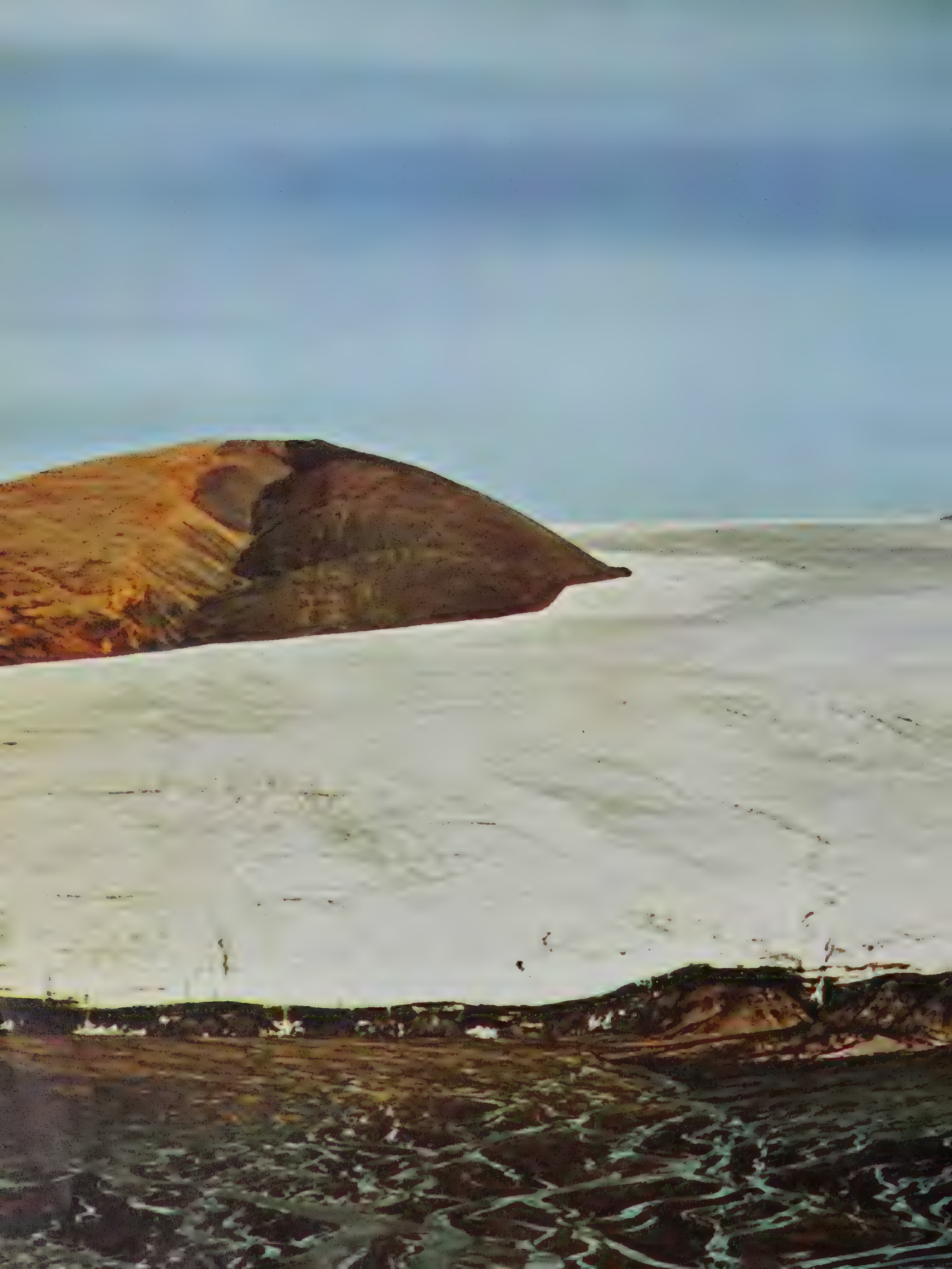
The work of glaciers in shaping the landscape is in some ways similar to that of streams. Both erode, transport, and deposit debris.

Moraines are left by glaciers at the sides and floor of the glacial trough. Large terminal moraines may mark the place in the valley where a glacier ended.

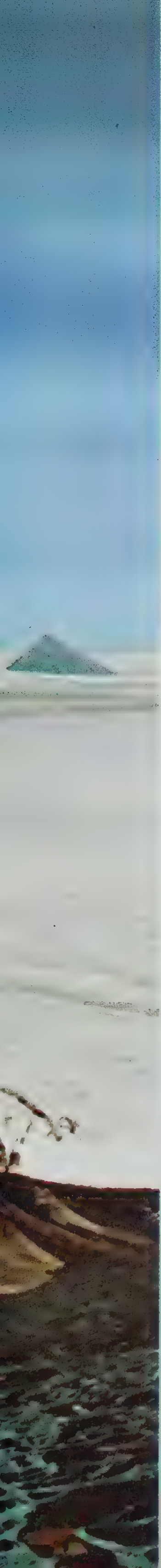
A glaciated landscape differs in several ways from one carved by streams. At the head of the glacier great cliff-walled cirques are formed, and the mountains may be spectacularly rugged. Mountains shaped by streams tend to be smoothly rounded. The valley of a glacier tends to have a U-shaped cross section whereas that of a stream is V-shaped. Once a glacier has disappeared, the streams of the region reshape the glacial valley and in time erase most of the evidence left by the glacier. Glacial valleys that meet the sea are called fjords. Icebergs are broken from the snouts of glaciers that entered the ocean.

REVIEW AND DISCUSSION QUESTIONS

1. Explain why the central part of a glacier moves faster than its sides or bottom.
2. Crevasses almost never extend to the bottom of a glacier. Why?
3. There are many spectacular valley glaciers in the part of the Andes Mountains that forms the border between Argentina and Chile. On which side of those mountains would you expect to find the larger glaciers? Why?
4. Contrary to what most people believe, there is less snowfall in the polar regions than in many other areas of the world. Explain why.
5. What is the relationship between solar energy and glacier formation?
6. An old hanging valley will often contain a waterfall. Describe how these "hanging waterfalls" may form.
7. A geologist sees a particular valley glacier for the first time. What observations could he make to find out whether the glacier is advancing, retreating, or standing still?
8. Fjords usually make good harbors. Why?
9. Why may there be glaciers in an area with an annual snowfall of 24 inches, while an area with an annual snowfall of 75 inches has none?
10. Very often a string of small lakes will be found in a vacated glacial valley. Explain how they may have formed.
11. A geologist observes a large valley glacier with four medial moraines. What can he expect to find as he proceeds toward the upper section of that glacier?
12. Most high mountains have a snow line, above which the snow never melts completely. What is the relationship between snow lines and valley glaciers?



glacial till land ore



CHAPTER 19

CONTINENTAL ICE SHEETS

Agassiz's suggestion that there had been other kinds of glaciers, different from those on mountains, attracted the attention of many geologists in America. These men were studying the region now called the Midwest and were trying to answer many questions about past glacial periods. They had to look for clues that would tell them where a glacier had been and when the glaciers had existed. They had to discover what changes had occurred because of the ice, and why the ice sheets had formed and disappeared. These early geologists found answers for some of these problems, but scientists are still seeking answers to others. Let us see what has been learned.

19-1 CLUES TO PAST ICE AGES

The continental ice sheets did not leave behind them such obvious clues as cirques and glacial troughs. Instead of filling valleys, the ice sheets spread over thousands of miles of gently rolling country. At one time or another, ice covered most of the land between the Appalachian Mountains and the northern Rockies, and northward from the Missouri and Ohio rivers. Ice flowed across New York, northern New Jersey, and New England, and onto what is now ocean bottom. Wherever the ice flowed, it left a clue—material similar to the ground moraine left by valley glaciers. In the regions once covered by the ice sheets, this is called **glacial till** (see Figure 19-1).

Glacial till is different from other transported debris. It is not uniform in texture nor is it stratified like stream and wind deposits. It is more like the material found in a landslide—a jumbled mass of unsorted debris. However, it differs from landslide debris in one very important respect. The pebbles, cobbles, and boulders in glacial till are somewhat rounded. The stones in a landslide are broken and angular. Glaciated

Continental ice sheet in the Canadian Northwest Territory

pebbles usually are faceted and sometimes show scratches on the flattened sides. Such flattening and scratching is not found on landslide stones.

As in the case of valley glaciers, the continental ice sheets left irregular piles of moraine at their edges. Great blocks of ice trapped in the moraine ultimately melted. Where this occurred, the debris above the ice settled and formed a depression in the moraine. Today some of these depressions, or **kettle holes**, are lakes or ponds, while others remain dry. This depends upon how porous the moraine was and how quickly the water drained from the depressions. Such a pitted moraine has a special name, **knob-and-kettle moraine**.

On the side of the end moraine away from the ice, meltwater carried and later redeposited the glacial debris. These deposits are partly sorted and are composed of obviously glaciated stones. To indicate their double source, glaciers and streams, they are called fluvioglacial outwash. Thousands of square miles of the upper Midwest are covered by this sort of debris (see Figure 19-1). Because such soil is composed chiefly of ground-up rock instead of weathered rock, it is excellent for farming. It has helped to make that region the breadbasket of our country.

Figure 19-1 Unsorted masses of rock ranging in size from sand to boulders make up the till that was deposited by ice sheets.

Figure 19-2 When the ice sheet retreated, its terminal moraine appeared as rounded, knobby hills and deep, closed depressions, or kettles, which often became ponds.

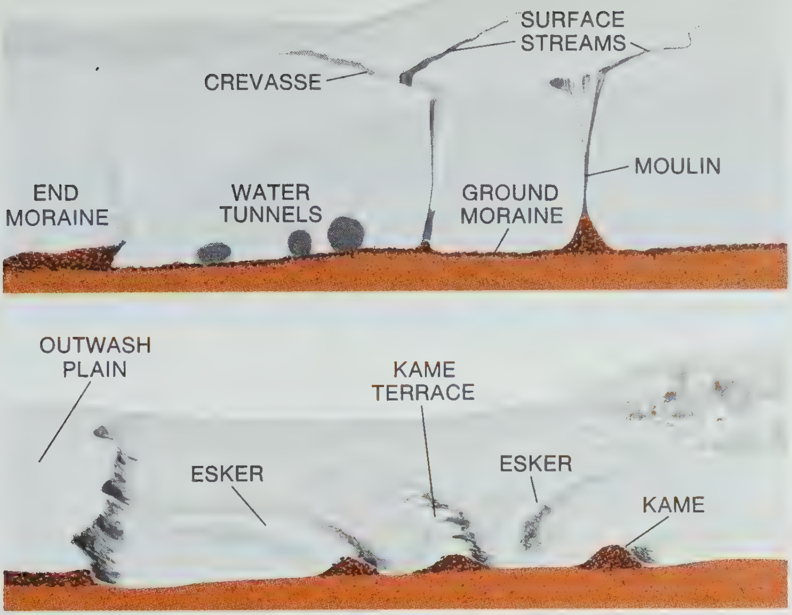


Figure 19-3 Debris deposited by glaciation and surface water built the type of features in this diagram—eskers, kames, and moraines.

On the side of the moraine that faced the ice, there are other clues to the past existence of the ice sheets. As the ice melted and retreated, lakes formed behind the moraines. When these drained, as most of them did, the old lake basins lined with stratified sediments were left behind.

In other places glacial debris was piled up under the ice. Near the melting end of the ice, cracks and holes (**moulins**) extended from the surface to the bottom of the ice. Meltwater washed debris trapped in the ice into these holes. At the bottom, the debris piled up into little hills that we call **kames** (see Figures 19-3 and 19-4).

Figure 19-4 An isolated kame in eastern Wisconsin. Kames are formed under glaciers by materials that fall in surface openings of a wasting glacier. Therefore, its material is stratified and sorted.

Figure 19-5 Eskers are ridges of stratified till less than 100 feet high. This esker winds several miles through swamps and lakes.

In still other places, streams of meltwater flowed under the ice. The sediment the stream carried piled up as the stream eroded its channel upward into the ice. This upward erosion of the ice occurred because the ice above the stream was less resistant than the stream bed. These under-the-ice streams thus constructed the winding *mounds* of clay, sand, and gravel that often cross swampy glacial till. Such snaky mounds are called **eskers** (see Figure 19-5).

Near Boston, Massachusetts, in the Mohawk Valley of New York, and in Ohio, Michigan, and Wisconsin are swarms of a third kind of glacial hill. These are elliptic in outline, steep at the northern end, and gently sloped at the other. They are largely composed of clay and are called **drumlins**. A famous swarm of drumlins is shown in Figure 19-6.

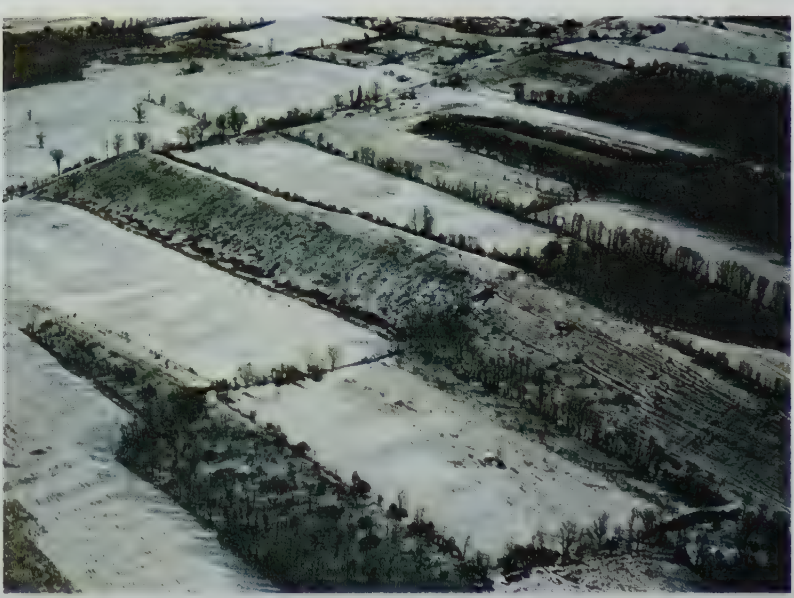


Figure 19-6 Drumlins appear in clusters, or swarms. As a glacier moved over its ground moraine, it molded large areas of it into elongated hills 50 to 150 feet high.

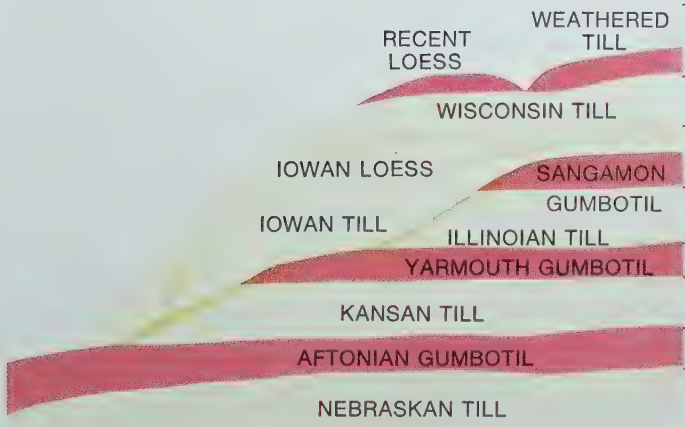
19-2 WAS THERE MORE THAN ONE PLEISTOCENE ICE SHEET?

Before the end of the nineteenth century, geologists studying the Midwest made a startling discovery. They found evidence that in the past not one but several great ice sheets had covered the land. They found this evidence in gravel pits and where roads and railways had been cut through low hills.

In such places, geologists found that there were several layers of glacial till, separated from each other by ancient soil layers (see Figure 19-7). They also noticed that the lower in the pile the layer of till was, the more weathered it was. Wherever this occurred, geologists reasoned that more than one ice sheet had covered the land. The material that separates the tills is a sticky, clayey soil called **gumbotil**, produced by weathering of glacial till. This discovery posed new questions: How long were the glacial stages, and how long were the warm, interglacial stages?

It took a long time to arrive at part of the answers to the questions posed by the sequence of glacial tills. It was not until 1931 that a first estimate was published. This was based upon G. F. Kay's studies of the weathered tills and the thickness of the gumbotils. Kay estimated the length of the interglacial stages, but could find no clues to the duration of the glacial stages. You will find his estimates in the first column of dates in Figure 19-7.

Figure 19-7 The dating of glacial and warm, interglacial stages by weathered till, called gumbotil.



Kay's estimate of duration in years of interglacial stage	Modern determination of number of years ago the glacial stage began
25,000	11,000
?	160,000
120,000	380,000
?	550,000
300,000	920,000
?	1,400,000
200,000	1,725,000
?	2,025,000

Kay estimated that it had taken 25,000 years to produce the degree of weathering seen in the most recent glacial tills. These tills had been produced during the glacial stage called the Wisconsin. The next lower tills are much more weathered. Kay decided that it had taken about 120,000 years to cause this much weathering. The names that are used for the glacial stages and for the warm, interglacial stages are based upon the places or regions where the evidence was first gathered.

Ten years after Kay published his estimates, Willard Libby, working then at the University of Chicago and now at the University of California at Los Angeles, discovered how to date organic material by the carbon-14 method (see Section 8-8). This has allowed us to date only the events of the last half of the Wisconsin stage. Why? By means of carbon-14 dating, we now know that the last great ice sheet started to retreat about 15,000 years ago, and by 11,000 years ago the ice was disappearing rapidly. Other scientists, using other methods, have given us information of when the glacial stages began and ended (see Figure 19-7).

Study Guide

1. Why is glacial till not layered and sorted?
2. How is glacial till different from landslide debris?
3. What is knob-and-kettle moraine?
4. How was the soil of much of the Midwest formed?
5. Name three land forms associated with ice sheets.
6. What is the evidence that ice sheets covered much of North America more than once?

19-3 WHAT WAS THE EFFECT OF THE ICE SHEETS ON RIVERS?

Much of the landscape that you see today, especially in the northern part of the United States and in Canada, is the result of the great Pleistocene ice sheets. Where the ice covered the land, the landscape is the direct result of ice action and recent stream erosion. Elsewhere, you may see the indirect result of the ice sheets.

Where the ice covered the land, it also covered the streams that flowed there. Usually these streams were blocked. Many of them disappeared. Others had to change their course. A good example is the present Missouri River. Before the Ice Age it was a smaller river system. To the west it drained parts

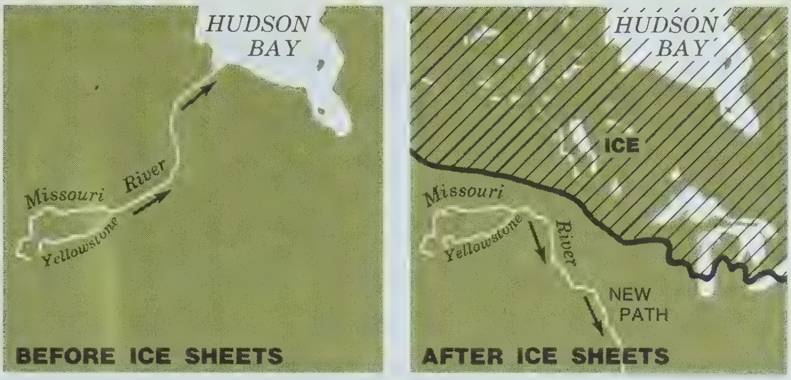


Figure 19-8 The Missouri River system before and after the Ice Age

of Kansas, Nebraska, and South Dakota (see Figure 19-8a). If this ancient river existed today, we probably would call it the Platte River system to the point where it joins the Mississippi.

All the rest of the present Missouri River drained northward, ultimately into Hudson Bay. Today only a small section of the United States drains northward, and this by the Red River of the North. The ice sheet turned the combined Upper Missouri and Yellowstone rivers from their northward course where they met the edge of the ice. It forced the rivers to flow southeastward along the margin of the ice (see Figure 19-8b). In this way, a huge area was added to the watershed of the Mississippi River system.

As the ice sheets melted, the Great Lakes region was uncovered earlier than the St. Lawrence River valley. This caused most of the water from the melting ice in the Great Lakes region to reach the ocean through the Mississippi River. Great as it is today, that river was even bigger during the retreat of the ice sheets. Other rivers farther east, such as the Mohawk and Hudson rivers in New York and the Connecticut River in New England, were equally enlarged. In the West, the melting ice made a giant river of the Columbia.

Not only the rivers were affected by the Ice Age. The desert regions of the Southwest—Utah, Nevada, New Mexico, Arizona, and southeastern California—were changed. During the Ice Age, they were not desert, but verdant grasslands and forests studded with hundreds of lakes. In the next chapter you will learn of other changes to the land brought about by the continental glaciers.

Figure 19-9 Great Salt Lake is all that remains of Lake Bonneville, a lake fed by the continental glacier during the Ice Age.

19-4 THE ICE SHEETS PRODUCED LAKES

In the semiarid parts of the West are remnants of some lakes that existed during the glacial stages. Great Salt Lake in Utah is one. It was once many times larger than it is now, and was filled with fresh water. This former lake was called Lake Bonneville (see Figure 19-9). It overflowed the low barrier of hills to the north and joined the Snake River, a tributary of the Columbia. As the ice disappeared and the climate warmed, Lake Bonneville shrank. Its surface was no longer high enough to flow into the Snake. As its water evaporated, the salts carried to it remained in the lake basin. Today Great Salt Lake is about ten times as salty as the oceans. Most of the lakes in the Great Basin (now western Utah and Nevada) dried up and are now salt flats.

In south-central Canada the retreating ice blocked the paths of rivers draining to the north. The oceanward flow of the water from the rivers and from the melting ice was blocked by the ice sheet. A huge lake, Lake Agassiz, was formed there. When the ice dam disappeared, the lake drained away into Hudson Bay. Left behind were hundreds of lakes, each in a basin scooped out of the rocks by the ice. The largest of these is Lake Winnipeg.

The most carefully studied lakes born of the glacial stage are the Great Lakes. We know little about their early history.

It seems probable that Lakes Superior, Michigan, and Huron were once river valleys contributing to a system that flowed into the Atlantic. These rivers probably joined the St. Lawrence River through the Ottawa River. Probably another river flowed through what are now Lakes Erie and Ontario. The history of the Great Lakes since the Wisconsin ice sheet is well known (see Figures 19-10 through 19-14).

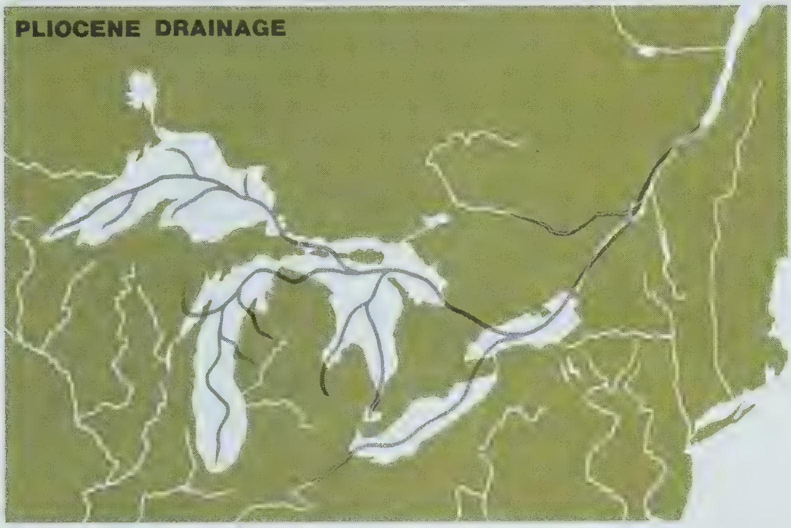


Figure 19-10 Estimated drainage of the present Great Lakes region during the Pliocene Epoch

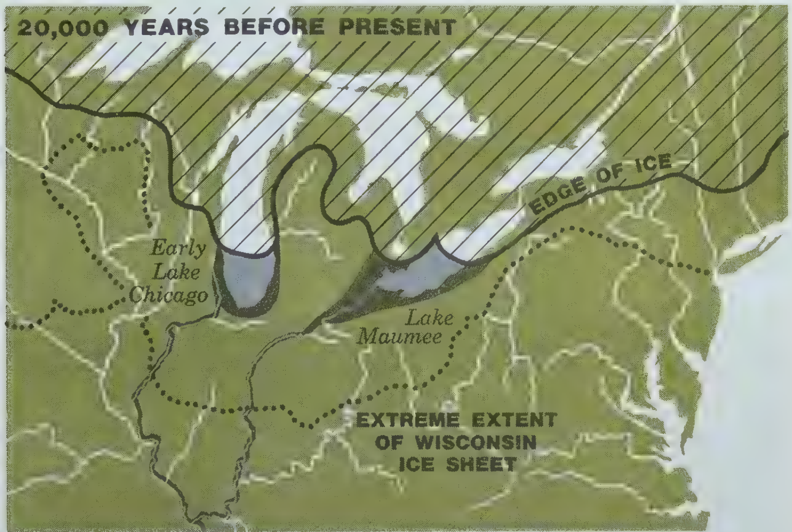


Figure 19-11 The Great Lakes region about 20,000 years ago

Figure 19-12 The Great Lakes region about 16,000 years ago

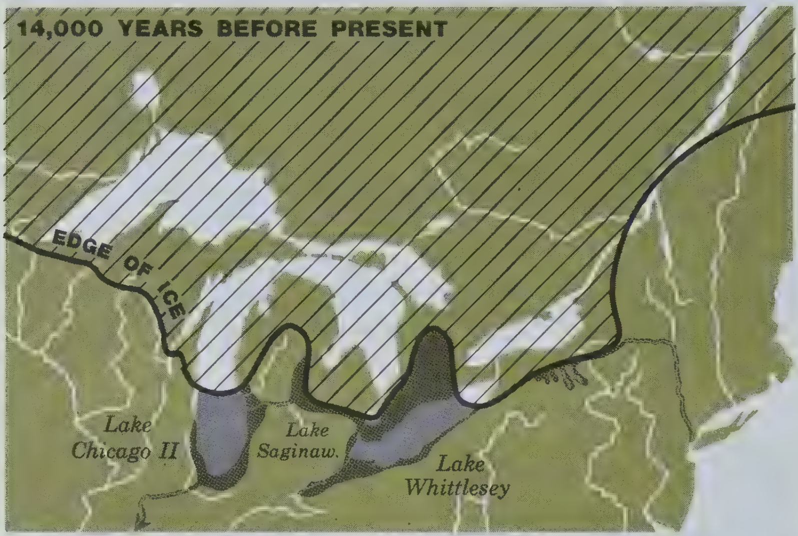


Figure 19-13 The Great Lakes region about 14,000 years ago

Figure 19-14 The Great Lakes region about 9,000 years ago

Study Guide

1. How did the ice sheets affect the rivers of North America?
2. What does Figure 19-10 show?
3. Study Figures 19-12 and 19-13 and describe what happened between 16,000 and 14,000 years ago.

19-5 THE EFFECT OF THE ICE SHEETS ON THE EARTH'S CRUST

Careful study of the history of Lake Michigan and Lake Huron during the past 10,000 years suggests that their lake basins have tilted. This tilting is still going on. The lakes once had a good outlet through the Ottawa River, which appears to have been raised too high to serve that purpose now. Let us search elsewhere to explain the tilting caused by the raising or lowering of the land.

What was the effect of the glacial ice upon the crust of the earth? Scientists know from laboratory measurements that the rocks of the crust have some flexibility. We know, of course, that ice has weight. How could these facts help explain movements of the crust?

Look at Figure 19-15, a map of the East Coast of the United States. Notice that south of 35°N the coastline is relatively smooth. A broad lowland stretches between the coast and the Appalachian Mountains. Between 35°N and 40°N the coast is peculiarly irregular. The sea seems to have invaded a series of river valleys leading to the ocean. What could account for this great difference?

Geologists believe there have been great movements of the earth's crust along the coast. The southern portion has been uplifted, and what is now dry land was once under water. The northern portion of the coast was lowered, and the ocean has invaded river valleys. Chesapeake Bay is an example of a flooded river valley. The whole East Coast appears to have been tilted. Other evidence of this tilting has been found in the old floodplains of the Connecticut River. The uppermost floodplains slope in a way that can be explained only if the mouth of the river was higher in the past than it is now.

Fishermen dredging for scallops far out at sea have brought to the surface quantities of peat. Peat is formed from mosses that grow in freshwater or brackish swamps. From this evidence it appears that the ocean bottom in and off the Gulf of Maine was dry land not long ago. That land is now under more than 100 feet of ocean.

Figure 19-15 The northern part of the East Coast of the United States shows evidence of sinking, and the southern part shows evidence of rising.

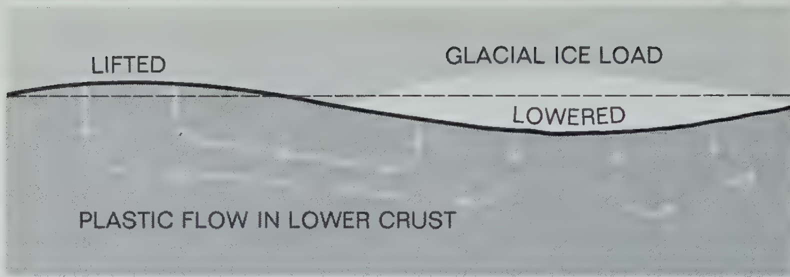


Figure 19-16 Isostatic reaction to glacial load

19-6 A THEORY

We have found evidence of tilting in the Great Lakes region as well as along the eastern coast of the United States. How can we explain all this evidence? Scientists believe the upper portion of the earth's crust rests upon a layer of material that is hot enough and under enough pressure to be somewhat plastic. This layer is therefore capable of flowing. How can this theory be used to explain the observed apparent tilting? Furthermore, how can all this information be linked with the Ice Age?

During the Ice Age a layer of ice several thousand feet thick rested on parts of the surface of the earth. What would the weight of this ice do to the crust? Our theory suggests that the crust would be forced down into the plastic layer beneath. The crust would then be out of balance. Where would the rock squeezed out from under the depressed, glaciated areas go? The only place where it could go would be outward, to an area of less pressure from above, as shown in Figure 19-16. If this happened, the region surrounding the ice sheet should have been pushed upward.

If this hypothesis is correct, it should explain what happened after the ice sheet disappeared. The weight deforming the earth's crust would have disappeared. With the loss of that weight, the crust was again out of balance. The uplifted area surrounding the depressed land was now too heavy. The plastic rock that had been forced under it began to flow back slowly to where it had come from. What evidence do we have from within the glaciated area to support our hypothesis?

Figure 19-17 shows where moraines were left around Hudson Bay by the retreating ice sheet 8,000 or 9,000 years ago. A thousand years later, almost all the ice behind these moraines had melted. At that time there existed a much enlarged Hudson Bay, called the Tyrell Sea. As the bottom of this sea rose, the shoreline retreated to its present position. The bottom of the former Tyrell Sea has risen 800 or 900 feet.

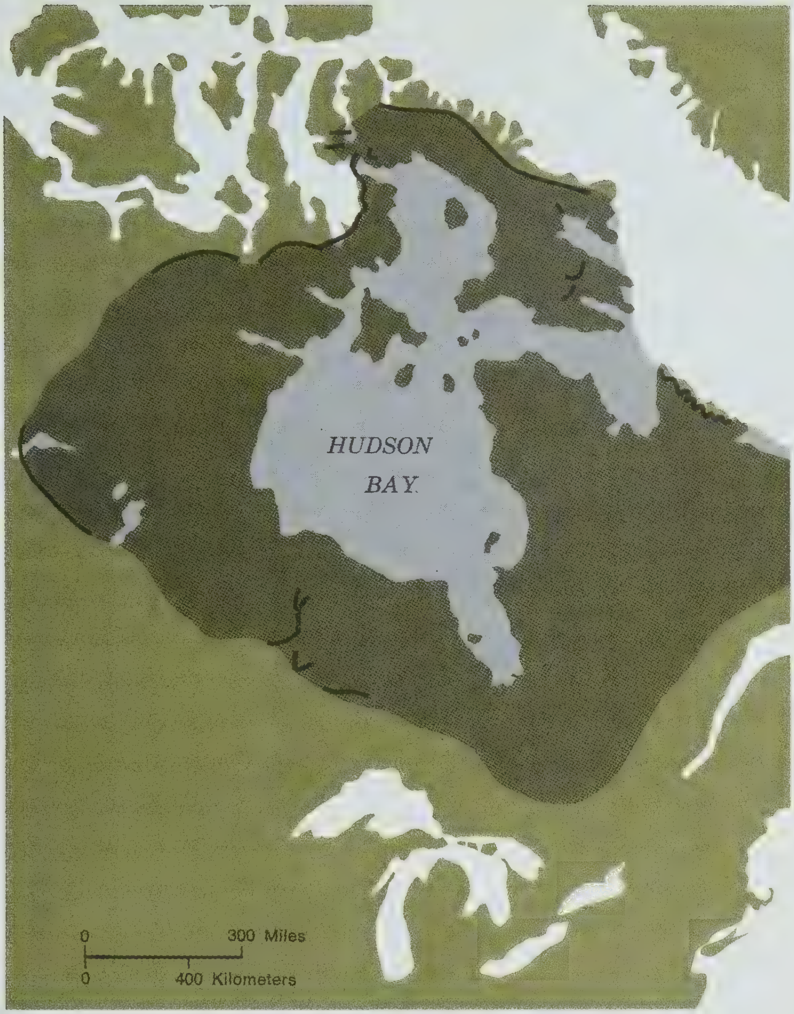


Figure 19-17 In the Hudson Bay area are moraines, which almost encircled the Late Wisconsin ice sheet, showing the limits of the Tyrell Sea.

The evidence for this are the old beaches on the eastern shore. They are now 800 to 900 feet above the present level of the bay. The floor of the bay has risen at an average rate of 1 foot in 10 years over the last 8,000 or 9,000 years!

Such long-range, slow adjustment of the crust to changing pressures is called *isostasy* (see Section 21-5). The theory of isostasy can explain the tilting of the basins of the Great Lakes, the tilting of the land along the East Coast, and the rising bottom of Hudson Bay.

19-7 THE ICE AGE AND THE OCEANS

What was the source of all the water necessary to form the huge Pleistocene ice sheets? It had come from the only source large enough, the oceans. Did the oceans shrink because of this? To find an answer to that question we must study what scientists have learned about the edges of continents and islands.

The coast is where the land and oceans meet. If the glaciers were responsible for much reduction in sea level, we should find the evidence of this at the coast. What kind of evidence should we seek? If the sea level were lowered appreciably for the duration of an ice age, there should be an old beachline now beneath the water. The ideal place to look is along the coasts of islands in the tropical oceans. Such islands are far enough removed from the glaciated areas not to have been affected by the weight of the glaciers.

Figure 19-18 The formation of an atoll

Charles Darwin was the first scientist to turn his attention to coral islands. He found that there were three kinds of such islands. One has a fringe of coral growing out from its shore as a **fringing reef**. Another has a **barrier reef** of coral some distance offshore. A third kind looks like a barrier reef with the island removed from within it. This kind is called an **atoll**.

The coral of all these islands is the remains of colonies of small animals that are related to jellyfish and hydra. The coral animals secrete a form of limestone as a protective housing. They require salty, clear, and warm water to thrive. They also require enough light to allow an alga that supplies them with oxygen to live with them. Because of these special requirements, reef-forming coral can live only where the ocean water is free of silt, warmer than 18°C (65°F), and shallow enough to allow light to penetrate.

Darwin suggested that the three kinds of coral islands are stages in the history of an oceanic island. First, an island is thrust up from the ocean bottom by volcanic action (see Figure 19-18). Coral animals settle near its shores and build a fringing reef. Because of local isostasy, the island slowly settles. As it does, the coral must grow upward to survive. A barrier reef is thus formed. In time, the island may disappear beneath the water, leaving only the barrier reef, now called an atoll. Where the island once was, there is now a lagoon. Darwin's theory has been supported, if not proved, by deep cores drilled into atolls such as Bikini. After penetrating thousands of feet of coral, which had once grown close to the surface, the rock core changes to basalt, which had once poured out of a volcano—as Darwin had predicted.

Figure 19-19 Torghattan Island, off the western coast of Norway, shows evidence of a sea level higher than the present level. The tunnel in the center of the island was cut by waves when the sea level was at that height. To the right and left of the tunnel are wave-cut benches.

Several scientists have carefully studied the structure of the coral reefs around islands. They have found that at about 100 meters (300 feet) below the present sea level there is evidence of an old beach, called a **wave-cut bench** or **marine terrace**. They believe this marks the level of the ocean during the Ice Age. Recently, other old coastlines have been found at about the same depth below present sea level.

For hundreds of miles along the west coast of southern Africa, there is an old coastline beneath about 100 meters of water. A similar coastline off the shore of Bermuda in the North Atlantic is at about the same depth. At Bermuda, William Beebe discovered the remains of stumps and roots of an old juniper forest close to the submerged shoreline. These were living trees about 11,000 years ago. This suggests very strongly that the old shorelines, now 300 feet beneath water, were the seacoasts when the glaciers started to retreat rapidly.

19-8 OTHER EVIDENCE

What changes would the withdrawal of 300 feet of water from the oceans make on the earth? In some places the change would hardly be noticeable. In others it would be marked. For example, the water that separates Siberia from Alaska is less than 300 feet deep. What now is the Bering Strait must have been dry land during the Ice Age. It connected Asia with North America. The English Channel is less than 300 feet deep. The British Isles were attached to Europe during the Ice Age. The islands of Sumatra, Java, and Borneo rim a sea that is also shallow. There, a large area that is now sea and islands was part of the mainland of southeastern Asia. Farther east, Australia and New Guinea were one landmass.

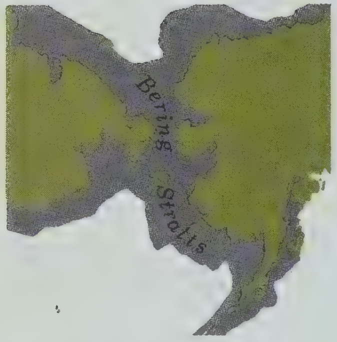


Figure 19-20 The lowering of sea level by about 300 feet would form a land bridge between Asia and North America. When the sea level was lowered by that amount during the Ice Age, early man migrated from Asia to North America across that isthmus.

Is there any evidence that these changes really occurred? Zoologists studying the animals of the islands of the southwest Pacific region have found that they are very similar to, and sometimes the same as, those on the nearby mainlands. They have found that some of the peculiar marsupial mammals of Australia are also common on New Guinea. Paleontologists studying the fossils from North America and the British Isles have found that during the Pleistocene Epoch those regions were invaded by several kinds of animals from Asia and Europe respectively. The evidence from zoology and paleontology supports that of the geologists. They reason that many areas now isolated by water were connected during the Ice Age.

Study Guide

1. How do we know that part of the East Coast has submerged?
2. How do scientists account for the lowering and raising of the East Coast?
3. Why are there old beaches 900 feet above sea level near Hudson Bay?
4. List some of the evidence that sea level has risen since much of the ice sheet of the Great Ice Age has melted.

19-9 WHAT CAUSED THE ICE AGE?

You have seen in the last two sections that the Ice Age affected the whole earth, not only the areas that were glaciated. What could have caused the formation of the huge ice sheets? Will there be others in the future? These are questions for which there are no good answers. We do not really know why there were ice ages in the Pleistocene and still earlier in the Permian Period and the Precambrian Era.

We do know the immediate cause for the continental glaciers and ice sheets: For a long time, more snow fell than melted each year. We know a few other things about the ice sheets. Just as mountain glaciers rarely start at the very top of a mountain, the continental ice sheets did not start at the North Pole. In North America the ice sheets originated in the vicinity of Hudson Bay. This is a region where now all the snow of winter usually melts away by the beginning of May. The climate there must have been quite different at the time the ice sheets began to form.

What changes in climate must occur before an ice sheet will form in the vicinity of Hudson Bay? It must be colder, and there must be more snow. At Churchill, on the west shore of Hudson Bay, enough precipitation occurs to produce about 15 feet of snow in a year. However, most of this falls as rain in the summer. The region receives enough energy in the form of insolation to melt about 64 feet of snow.

What could increase the amount of precipitation at Churchill? If warm, moist maritime air could move farther north than it does today, precipitation would increase in this region. Probably the most effective cause for this movement would be a reduction of the strength of the polar high. One way that this could happen has been suggested by Maurice Ewing and William Donn. They believe an ice age could begin if the Arctic Ocean were free of ice and warmer than it is at present. This would greatly reduce the size and strength of the polar high. Unfortunately, there is no adequate explanation of how the Arctic can be freed of ice.

If the polar high were reduced, the great warm, moist maritime air mass that pushes up the Mississippi Valley would reach far north. It would carry large quantities of water vapor into the Churchill area. This might increase precipitation there to about 30 inches a year. But that is only half the amount needed for an ice sheet to form. However, if at the same time insolation were reduced by 5 to 10 percent, snow would accumulate and an ice sheet might form. How is it possible for a climate to change?

Many suggestions have been made as to how the amount of energy reaching us from the sun might have been reduced. One of these suggestions is that a sort of "sunshade" was introduced between the sun and the earth's surface. Some scientists suggest that the atmosphere was filled with dust from a long period of volcanic eruptions. Recently, evidence of this was found in the Antarctic. Others believe the amount of carbon dioxide in the air has changed. A few have

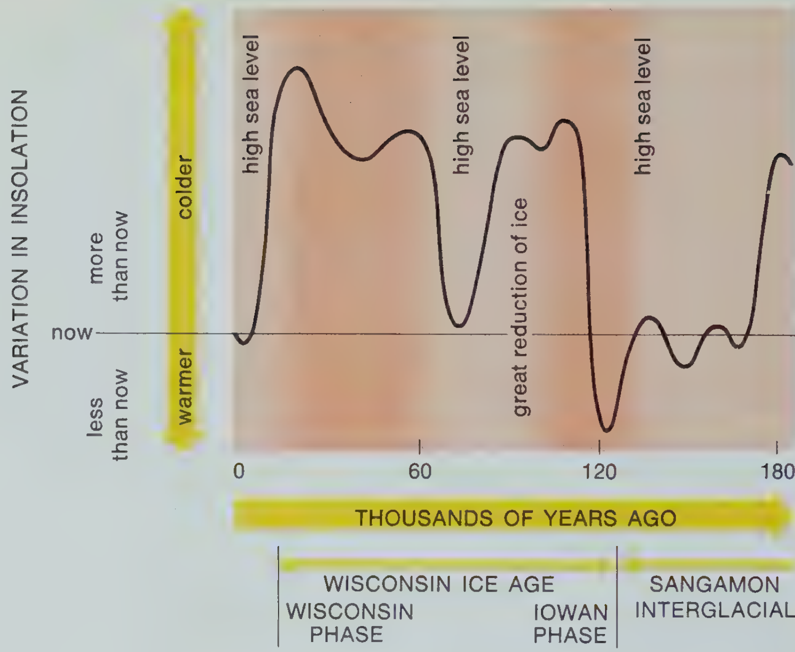


Figure 19-21 Graph showing the variation of insolation and of sea level with time

suggested that the solar system periodically passed through a great cloud of cosmic dust. Today the last of these hypotheses is perhaps the only one seriously considered as a cause for ice sheets.

William Broecker of the Lamont Geological Observatory has suggested that the recent Pleistocene ice sheets are the results of slight changes in the angle of tilt of the earth's axis and precession. He calculated the effects of these changes on insolation. Figure 19-21 shows his data plotted as a graph. The curving line indicates when insolation (according to Broecker) was greater or less than it is today. When we add to his graph information about the glacial ages, there appears to be a close relationship between the two sets of data.

It seems inviting to say that this answers our problem about what caused the Ice Age. However, scientists are cautious. What Broecker learned may have contributed to an ice age, but no one is willing to say that it caused one. One reason for this caution is that the sun and the earth have been going through the same cycles for millions of years. But ice ages have occurred at only very widely spaced periods in the whole history of the earth.

The only conclusion we can reach is that although scientists know the conditions that would cause an ice age, they do not know what would bring about those conditions.

19-10 HOW THE CONTINENTAL GLACIERS MOVED SOUTHWARD

Valley glaciers move downslope under the influence of gravity and the plastic flow of the ice. The continental ice sheets had no continuous slopes down which to flow. They moved across relatively flat country, rode over hills and valleys, and even pushed their way over mountains in New York and New England.

There are two principal ways the continental ice sheets extended themselves. One of these is plastic flow, similar to that of a valley glacier. Once ice accumulates to a depth of about 50 to 60 meters (about 180 feet), the pressure upon the ice near the bottom makes it plastic. This plastic ice flows outward from the region of greater pressure to the surrounding areas of less pressure. The thicker the ice sheet is, the higher the obstacle it can overflow. It appears probable that the ice sheets were as much as 10,000 feet thick. This explains how the continental ice sheets were able to run over mountains several thousand feet high.

Another way ice sheets moved southward is by a kind of growth. This growth occurred mostly toward the south. The Pleistocene ice sheets grew because of the moisture-laden winds blowing up the Mississippi Valley and in from the Atlantic Ocean.

The air in the maritime tropical air masses is warm. This means they contain a great deal of water vapor. When these air masses move up to and over the ice, they meet cold, dry air in the glacial high. The result is obvious. The warm air is chilled and loses its moisture. During the Pleistocene, moisture fell as snow and added to the southern portions of the ice.

The ice sheets grew southward until they extended into a latitude where insolation was too high for them to exist. At that latitude as much snow melted each year as fell. The whole glacier could not grow farther south, although tongues of ice did flow farther south. The ice sheets ended where the melting equaled the amount of ice pushed forward each year. What was the country like just south of the ice fronts? You will read about that in the next chapter.

Study Guide

1. Where was the origin of the ice sheet in North America?
2. What two factors would have to change before another ice sheet could form?
3. How might a reduced polar high-pressure area affect snowfall in central Canada?
4. How could the amount of incoming solar radiation be reduced?

SUMMARY

Earth scientists have found a number of clues that indicate where continental ice sheets once existed. These clues are the unsorted layers of glacial debris called glacial till. Most of this till is spread across the land as a sheet. Here and there some of it is piled into kames, eskers, and drumlins. Glacial action changed the drainage system of the region under and adjacent to the ice sheets. Lakes formed in basins wholly or partly excavated by the ice.

Far from the ice front, changes in the climate altered the appearance of the land. Forests, grasslands, and lakes existed where there now are semiarid regions. During the glacial stages, rivers that drained the ice front, such as the Mississippi, were much larger than they are today.

The weight of the ice threw the earth's crust out of balance. The balance was regained through isostasy. This action tilted parts of the continent and changed the relationship between land and sea. The withdrawal of about 100 meters of water from the oceans also affected this relationship. The glaciers in the Northern Hemisphere during the Pleistocene had a worldwide effect on sea level.

Scientists are still searching for the causes of glacial ages. They are seeking the reasons for the cooler and moister climate that seems necessary to form an ice sheet. It appears probable that an ice-free Arctic Ocean reduced the extent and strength of the polar high.

REVIEW AND DISCUSSION QUESTIONS

1. Describe how you can distinguish between alluvium, glacial till, deposits from landslides, and windblown deposits.
2. Under what conditions would you find glacial debris in layered deposits?
3. Why is it reasonable to believe that kames, eskers, and drumlins are landforms produced by the last ice sheet?
4. The material of which eskers are formed is stratified, but these structures stand up above the surrounding terrain. How do you explain such a curious situation?
5. What evidence do we have of more than one ice sheet?

6. How have estimates been made of the time for each of the Pleistocene stages of glaciation?
7. Why are geologists more certain of interglacial durations than of glacial durations?
8. Along the shores of some of the Finger Lakes in New York, there are traces of an old shoreline some distance above the present surface level of the lakes. This shoreline is not parallel with the present level of the lakes but dips toward the south. Try to explain the old shoreline and its dip.
9. If you were exploring the Great Basin, what evidence would you use to map the location of lakes that had existed during the Wisconsin glacial stage?
10. There is evidence that the crust of the earth in North America has not yet fully recovered from the effects of the last glaciation. How could full recovery of the crust from the weight of the ice change the direction in which Lake Michigan drains into the ocean?
11. Churchill, Manitoba, receives 95 kilolangleys of solar energy a year, but only 13 kilolangleys are available to melt snow. What might happen to the rest of the solar energy?
12. The air over a glacial mass is cold and dry. Explain why this situation increases snowfall along the southern edge of a glacier.

CHAPTER 20

BETWEEN GLACIER AND FOREST–DESERT

Many people imagine that during the Ice Ages our continent was an arctic wasteland. Nothing could be farther from the truth. In the southern part of the United States, great forests extended far into areas that are now treeless grasslands. In and around these forests lived the same kinds of animals that we find living on the continent today, as well as some that are now extinct. Today there are no longer any mammoths or tree sloths, and there are fewer kinds of pronghorns and bison. Skeletons of these extinct animals have been found in the alluvium deposited after the Wisconsin ice sheet started to melt.

The kinds of plants and animals that today live in Canada and the northern United States lived then in the forests and grasslands south of the ice sheets. During the Ice Ages, forest occupied the lower Mississippi Valley, from Alabama to central Texas. It differed from the Gulf Coast forest of today, for it contained the same kinds of plant life we now find north of the Great Lakes. Similarly, the part of the forest along the southeastern coast of the United States was a type now found in northern areas. How close was the forest to the front of the glacier? What was between the forest and the glacier? These are questions to investigate.

20-1 THE TUNDRA

Explorers in the subarctic and arctic parts of North America have supplied us with good descriptions of areas where the climate is too cold for trees to grow. The forest of northern Canada does not come to an abrupt end. Rather, the trees get smaller and smaller as one goes farther north. In sheltered areas they extend farther north than in exposed areas. The coniferous forest gives way to shrubby willows and alders. Still farther north, plant life becomes even smaller and almost disappears.

Many deserts of today were created by the atmospheric conditions of the past that produced glaciers.

Figure 20-1 The tundra can be a garden by the ice. Many low and flowering plants grow in the tundra, depending on the altitude. The soil is thin and rocky, with a permanently frozen subsoil.

The land covered only with scattered grass and sedges is called **tundra** (see Figure 20-1). In the far north, tundra can be found wherever land is free of snow in the summer. Even in this cold land, many flowering plants push up through the melting snow in early summer.

It is probable that the land adjacent to the ancient glaciers resembled the polar regions of today. However, the distance between the ice sheet and the forest was much less. Instead of being measured in hundreds of miles, as it is now, it was measured in tens of miles. Figure 20-2 shows the relationship of the glaciers and the forest.

Botanists estimate that in the Mississippi Valley the forest approached within 50 miles of the ice and was well developed only 100 miles south of the glacier.

Figure 20-2 The location of the edge of the ice sheet and the forest during the Great Ice Age

Figure 20-3 In the Great Sand Dunes National Monument in Colorado, there are hills of sand held in place by grasses.

20-2 A COLD DESERT

The Great Plains of today contain evidence that between the tundra and the ice sheet there were open expanses of cold desert. This was a region with little vegetation. It appears to have been covered by fine silt and sand blown there by winds. This loose material came from the fluvioglacial outwash near the ice and along the rivers that flowed from it.

In northeastern Colorado, in northwestern Kansas, and north and south of the Platte River in Nebraska, there are hundreds of square miles of ancient sand dunes now held in place by grasses. Figure 20-3 shows such a region. Similar windblown soil is abundant on the east bank of the Mississippi River from Illinois southward. Such windblown soil is called **loess**. It is composed of particles smaller than average sand grains. Much of the loess deposited in the central part of the United States is windblown fluvioglacial outwash.

loess (les).

Why should great areas of loess be associated with the continental glacier? We usually associate blowing sand and sand dunes with hot deserts, not with the cold fringes of a land covered by ice.

Study Guide

1. Where in the United States did the kinds of plants and animals now living in Canada probably live during the Ice Ages?
2. What changes occur in the kinds of plant life one can observe as one gets closer to the polar regions?
3. Describe tundra.
4. What is loess?

20-3 SAND DUNES

To discover why there were great stretches of sand dunes near the southern edge of the ice sheet, we must investigate how sand dunes form. Where do we find sand dunes today? We find them wherever there is finely divided material not held in place by vegetation. The mere presence of this material will not cause a sand dune. There must be winds that are constant and strong enough to blow sand into piles.

Air is a fluid, but it differs from liquids in that it is less dense. When air moves, it has the capacity to do the same things that moving water does. It erodes, transports, and deposits. You may never have noticed moving air (wind) doing any eroding, but all of you have seen it carry things and deposit them.

The carrying capacity of wind is like that of water. As wind slows, it drops part of its load because of the loss of kinetic energy (see Section 17-2). When wind moves over or around an obstacle, energy is needed to lift the air molecules. Therefore, less energy is available to carry debris. Where a steady wind carrying silt and sand drops its load, material will accumulate. If wind drops silt and sand in the same place most of the time, a sand dune may form.

20-4 SAND DUNES AND A GLACIER

Can we expect to find a large supply of finely divided material and a steady wind near a glacier? Glacial outwash contains much finely ground rock. This is washed away from the glacier front by meltwater and deposited as alluvium. As long as

Figure 20-4 Melting glaciers leave a jumble of rocks, pebbles, sand, and rock flour, which is eventually washed or blown away from the front of the glacier.

this material is wet, it does not blow away. Since glaciers melted only during the warmest months of the year, it seems probable that for six to eight months there was little or no melting. This long dry period would allow the outwash to dry. Thus, we have a source of transportable material.

Next, we need to know whether vegetation was present to hold these particles in place. What do plants need in order to grow? In addition to sunlight, they need soil, moisture, and warmth. Directly in front of the glacier there was plenty of good soil and moisture, but there was not much heat. The glacier acted like a huge refrigerator.

The warmest period was also the period when meltwater was running over the outwash. Plants cannot grow under such conditions. By the time the outwash had dried, the temperature was too low for seeds to sprout. Thus, we can assume with confidence that near the glacial ice there were great expanses of sand and silt with little or no plant cover. This condition is ideal for the making of sand dunes, provided there is a steady wind.

Is there any good reason for believing there was a steady wind blowing close to the glacier? Wind is air moving from an area of high pressure to one of low pressure. Highs occur where the air in a particular area is denser than the surrounding air. As air cools, it increases in density. Where is the densest air in the vicinity of a glacier? It is right on the glacier. This is one of the factors that helps the glacier to endure. The cold, dense air causes a permanent glacial high. Therefore, at all times winds will be blowing away from the glacier (see Figure 20-5).

Figure 20-5 The air-pressure system over a glacier tends to produce a wind blowing away from the glacier.

Will glacial winds blow with the same velocity all year? The speed of a wind, and therefore its power to erode and transport, depends on the steepness of the pressure gradient between the high and the low. If over a distance of a hundred miles there is little difference in air pressure, winds will be gentle. If, on the other hand, there is considerable difference in pressure over that hundred miles, winds will be strong.

In the winter months the temperature difference between the glacier and the forest is slight; therefore the winds will be weak. In the summer, when the forested area is warmed by the sun, there will be a greater temperature and pressure difference; so there will be stronger winds.

As the forest area begins to warm in the spring, the winds blowing from the glacier will increase in strength. Until the outwash becomes saturated with meltwater, the winds will carry large quantities of silt away from the glacier. Over the tundra, the wind from the glacier will be warmed and will start to rise. The wind will lose some of its kinetic energy, and it will drop some of its load.

Thus, year after year, in the spring and possibly in the fall, winds from the glacier transported silt and deposited it between the forest and the ice sheet. In this way, we believe, enormous amounts of loess were deposited south of the ice sheets—in North America, in southeastern Europe, and in the Gobi desert regions of China. The major loess deposits in the United States are outlined on the map (Figure 20-6).

Figure 20-6 Loess deposits in the United States

Any area where finely divided material is formed and a protective plant cover is lacking can supply material to produce loess deposits. Rivers that cover a broad floodplain each spring have loess deposits near them. So do semiarid lands such as those in the Southwest.

During the glacial stages, winds probably swept up fine silt from the floodplain of the Mississippi River. Such winds deposited the silt as loess along the river terraces (see Section 16-10) to the east. Each of the large streams that cross the plains in Nebraska, Colorado, and New Mexico has loess deposits along its northern banks. These riverside loess deposits are very fertile. When moistened by rain or irrigation, they support good crops.

In Idaho, Washington, and Oregon there are similar deposits along the Columbia and Snake rivers.

Study Guide

1. Explain why winds during the Ice Ages blew away from the glacier.
2. During which season were the strongest winds blowing away from the glaciers? Why?
3. What effect did the plant life of the southwestern United States during the Ice Ages have on the formation of the present-day deserts in that area?
4. Describe the conditions necessary to allow the wind to transport material away from the glacier.

20-5 DESERTS

When we hear the word *desert*, we usually think of a great sandy wasteland covered with huge crescent-shaped sand dunes. Sometimes our imagination populates the desert with Arab sheiks wearing loose white robes and racing across the sand on swift camels. This is the desert of movies and television, not the most common type of desert.

Most dictionaries define a desert as a place with so little moisture that there is only sparse, widely spaced vegetation. This is a good definition, but it does not tell us much about the climatic conditions that cause a desert. Geographers have defined a desert as any region with less than 10 inches of precipitation a year. In warm, desert regions, such as in Arizona, the dry air evaporates so much of the scanty precipitation that little moisture is left for plants (see Figure 20-7).

Since 1950 an entirely different kind of desert has been studied—the cold, polar desert. In the polar deserts, much less evaporation occurs, leaving more moisture for plants. The land in northern Canada that lies between the northern

Figure 20-7 Death Valley is a hot, dry desert. Its lowest point is 285 feet below sea level, and it is rimmed by mountains 2,000 feet above its floor.

Figure 20-8 In the spruce forests of the Arctic are immense, low-lying, swampy areas known as muskegs. Such land is poorly drained because there are few rivers.

edges of the forest and the Arctic Ocean receives between 9 and 11 inches of precipitation a year. This region, called tundra, would be a desert by the geographer's definition. Although the region is treeless, low-growing plants form a mat on the soil (see Figure 20-1).

In the Canadian tundra there are huge lakes and thousands of square miles of a peculiar kind of arctic swamp called **muskeg**. Such conditions, shown in Figure 20-8, are not those that we usually associate with a desert. As soon as the late spring sun melts the snow, water gathers in shallow pools thickly studded with high clumps of sedges and grasses. Low, stunted willows, alder, and members of the blueberry family form clumps of bushes in the wet landscape.

The drainage pattern in this cold land is poorly developed. There are no organized stream systems to carry off the water. The condition of the undersoil also helps form the muskeg. The whole countryside is underlain with frozen soil. A perpetually frozen layer of undersoil is called **permafrost**. It never thaws, so the water from the melted snow cannot sink into the ground.

The water table over great expanses is actually at ground level. Therefore the region is not desertlike; if anything, there is too much water. The three factors responsible for this situation in a region of low precipitation are a very low rate of evaporation, poor drainage, and permafrost.

20-6 HOW A WARM DESERT MAY DEVELOP

The deserts of our Southwest were not always deserts. You will recall that during the Ice Ages there were many lakes in those regions. At that time, precipitation was greater than it is now, and the cooler air reduced evaporation. At the close of the Pleistocene Epoch, as the ice sheets melted, the Southwest became warmer and drier. Deserts developed there. Many of the rocks now found in these regions were formed millions of years ago from deposits of windblown sand. Such deposits are evidence that deserts were there in past ages.

As the deserts developed, many of the plants did not receive sufficient moisture and died. During the drying period, the streams no longer contained surface water all year. They had water only when it rained or, if they were close to high mountains, when the snow melted in the spring. Only those plants living along the channels of streams, with roots penetrating deeply into the soil, were able to survive.

Modern desert plants such as cactus, agave, yucca, and ocotillo grow widely separated from one another and do not shed enough leaves to produce a humus layer. Thus, these plants give the soil very little protection against erosion.

Winds whipping across the dried land carry away the finer particles, leaving a surface layer of pebbles and coarse gravel. Most deserts are not sandy; they are like the **stone-paved** desert shown in Figure 20-9.

Figure 20-9 Geologists refer to a stone-paved desert as a *hummada*, from the Arabic.

Figure 20-10 The shade of palm trees and spring water make an oasis a refuge for desert travelers.

The pebbly surface of the desert helps the desert plants live and grow. At night, when it gets cold on the desert, these pebbles also get cold. What little moisture there is in the air condenses on them as dew. This tiny bit of water trickles over the smooth stones and into the soil beneath them. It is this bit of water, together with the water from infrequent rainstorms, that supports the plant and animal life of the desert.

Widely scattered on a desert are places where the water table comes close enough to the surface to allow a group of trees to exist. Such a place is called an **oasis**. Wells are dug or drilled there to bring water to the surface. Figure 20-10 shows such an oasis.

Study Guide

1. The polar regions are sometimes called cold deserts. What climatic factors control the formation of deserts?
2. What effect does permafrost have on plant life?
3. Explain why great areas in hot deserts are stone-paved rather than sandy.
4. Describe the muskeg and how it forms.
5. What is an oasis?

20-7 THE SANDY DESERT

Most desert areas are stone-paved, but there are also many sandy areas. In every desert, there must be some places where the wind drops the fine particles it has removed while producing the stone pavement.

Figure 20-11 Sand dunes migrate across the land, depending on the force and the direction of the wind.

The sandy parts of a desert are not smooth; they are covered by low, rolling hills of sand called **sand dunes** (see Figure 20-11). These sand hills do not remain stationary, but slowly move across the country in the direction of the winds. They move just as sand dunes move along a beach. The wind blows the sand grains up one side of the hill, and they roll down the other. In time, the whole sand dune has changed position.

The shape of sand dunes depends on the strength of the wind. When it is just strong enough to form dunes, these moving hills extend at right angles to the direction of the wind. Because they lie across the path of the wind, they are called **transverse dunes**. Where the wind is much stronger, the dunes lie parallel to the direction of the wind and are called **longitudinal dunes**. Figure 20-12 compares transverse and longitudinal dunes.

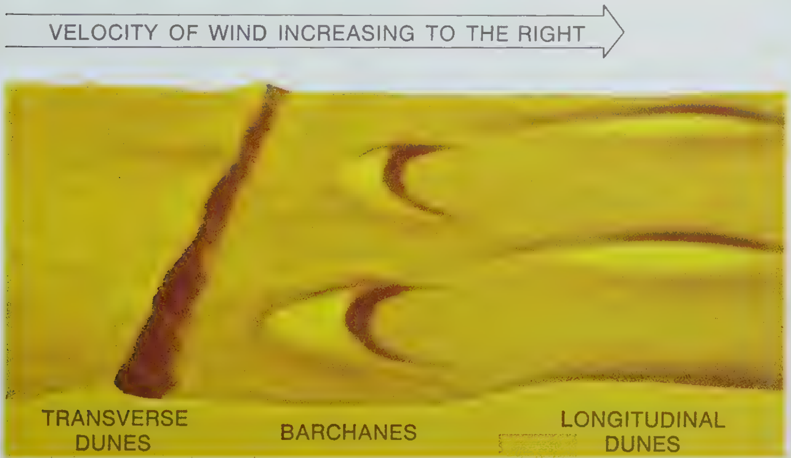
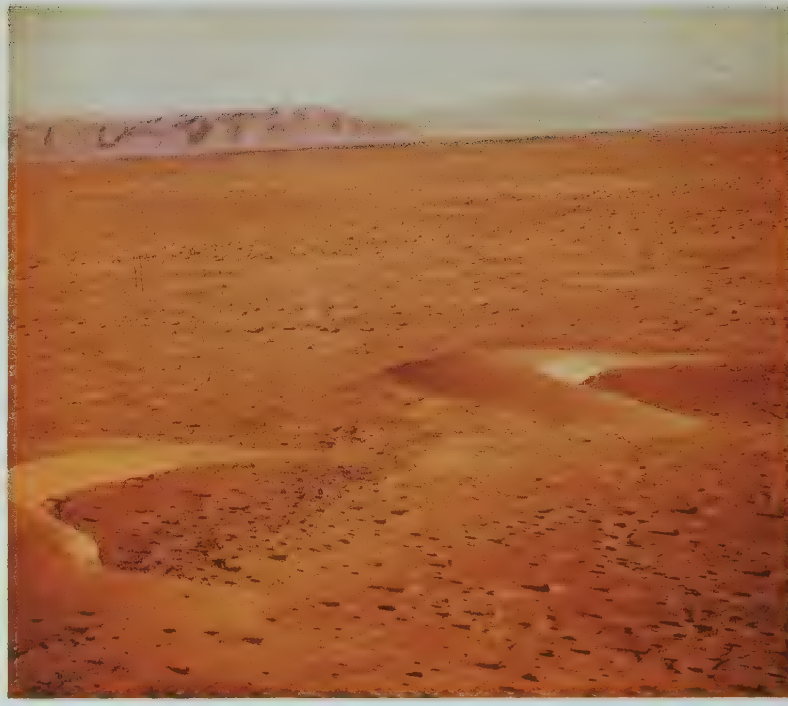


Figure 20-12 The development of transverse and longitudinal dunes depends on the force and direction of the wind.

Figure 20-13 The horns of the barchan point downwind, in which direction they move at a rate of 25 feet to 50 feet a year. Their formation requires a wind from a fixed direction and a hard, flat surface.



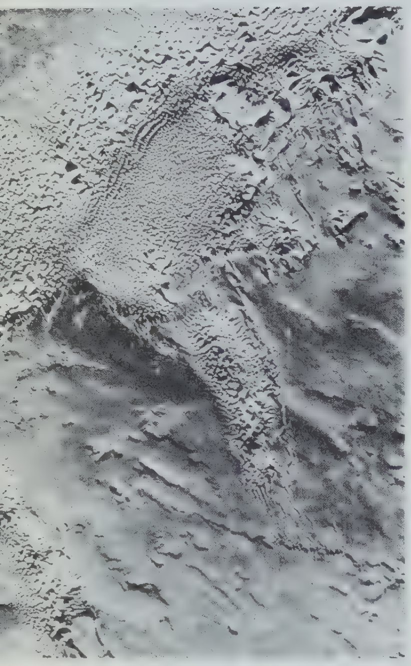


Figure 20-14 A giant seif surrounded by stone-paved desert. Seifs are often up to 300 feet high and may extend for 60 miles.

Crescent-shaped dunes are the rarest kind. To form them, the wind must have just the right strength and must blow steadily from one direction. Such a dune is called a **barchan** (see Figure 20-13). A barchan starts as a short but high transverse dune. As the wind meets this obstacle, part of it moves over the dune and part of it sweeps around the ends. The wind that goes around the ends causes short bits of longitudinal dune to form, attached to the ends of the transverse dune. In time, the wind smoothly rounds the entire outline of the dune into a crescent, with the convex side toward the wind.

In some regions, the sand dunes of a desert may be massed together in a huge pile. Such an accumulation of dunes is called a **seif** (see Figure 20-14). Seifs are formed when the winds from one direction are carrying a heavy load of sand and are met by opposing winds of stronger force.

seif (sayf). A spectacular seif in the United States is in the Great Sand Dunes National Monument in Colorado.

The surface of gently rolling sand hills, and of some dunes, is often rippled. This is best seen soon after a rain shower, when the crests of the ripples have dried but the hollows between them are still moist. The light-colored, dry sand then contrasts with the darker, moist sand.

A feature of windblown sand that one can use to recognize sandstones made from land deposits rather than sea deposits

is called **cross-bedding**. The sand that rolls down the sheltered, leeward side of a dune is stratified. The strata lie at an angle away from the direction of the wind. On the other side of the dune, the windward side, similar strata form but lie at a different angle.

In a stationary dune, the strata are arranged as shown in Figure 20-15. However, few dunes are truly stationary. Most of them migrate. As a result, what had been the leeward side becomes the windward side. There the strata of newly dropped sand lies at an angle to the strata of the old leeward-side sand.

Study Figure 20-16 to see how cross-bedding occurs. This photograph also tells us that the region was arid millions of years ago, when the sand was originally deposited.

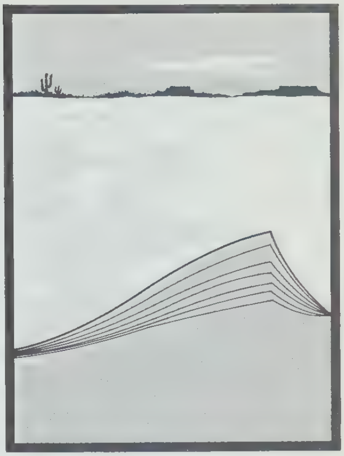


Figure 20-15 A dune moves downwind when the angle of the steep lee slope increases beyond 35 degrees and sand grains slide down the slope.

20-8 WATER ON DESERTS

The warm or hot desert regions are found where there is not enough precipitation to support the plant cover necessary to protect the loose surface material. There is no place on earth

Figure 20-16 Sandstone showing cross-bedding indicates the existence of a former desert. Excavations through sand dunes reveal more complex stratification than is found in lake sediments.

where it does not rain or snow at some time. The driest regions—the deserts along the coasts of Peru and Chile and the great deserts in Africa, Asia, and Australia—may not receive rain for several years at a time. In the United States the deserts all receive at least 3 inches of precipitation a year.

What happens to this rain depends on the kind of desert. On a stone-paved desert, some of the water soaks into the upper inch of the hard-packed soil. But most of it runs off and forms pools in surface depressions.

The water that gathers in pools carries with it a muddy alluvium, which is deposited on the bottom of the pool. As the water evaporates, the mud is exposed to the air, and dries. Most of the mud particles are clay minerals, and these absorb water into their structure. When the particles dry, they lose this loosely held water and shrink. The results are **mud cracks**, shown in Figure 20-17.

playa (PLY uh); Spanish: beach.

Sometimes these temporary desert pools are extensive and can be called "lakes." The dry bed of one of these "lakes" is called a **playa**. Several of the playas on the deserts of the

Figure 20-17 When fine-grained sediments of a playa dry out, they form cracks that make polygonal patterns.

Figure 20-18 Alkali ponds in a desert. Notice the white precipitated salts around the edge of the ponds.

Southwest have been repeatedly filling with water and evaporating to dryness for thousands of years. The alluvium of such lake bottoms contains not only silt and clay particles but also all the salts that had been dissolved in the water. Most of these salt-lake deposits are composed of the salts found in ocean water.

A few playas contain deposits of unusual salts. For example, the rocks that form the southern rim of Death Valley in California contain minerals rich in boron, one of the less common chemical elements. Each rainstorm carries a little of this element from the weathering rocks to the playa at the foot of the mountains. The result is a deposit of borax, which contains boron, in the alluvium of the playa. For many years the lake bottom was mined for its borax. Today we extract the borax from its source in the rim of the valley.

Other dry-lake beds are rich in potassium salts derived from the weathering of feldspars and micas. These beds, too, are mined for their mineral resources.

On a sandy desert, almost all the rain immediately soaks into the loose surface sand and slowly sinks through the more compact sand beneath. Some of the water sinks all the way through the sand cover and reaches an impervious layer, usually clay. The water then creeps downslope along that layer.

In places where the wind has removed enough sand to expose the clay, the water emerges from underground and may form a temporary pool or small lake. Such pools fill with water during the rainy season, if there is one, and then lose most of the water through evaporation. A few, such as those shown in Figure 20-18, have such a steady supply of water that a small pool is able to exist from one rainy period to the next. The water in these pools usually contains so much dissolved mineral matter that it tastes bitter or salty.

Study Guide

1. How do sand dunes move?
2. What determines the shape of a sand dune?
3. What is a playa?
4. How can cross-bedding indicate that a particular rock deposit was formed on land rather than under water?
5. What was the origin of the rich borax deposits of our western deserts?

SUMMARY

There are several kinds of desert—cold or warm, stonepaved or sandy. Each is the result of the balance between precipitation and evaporation. During the Ice Ages, cold, sandy deserts formed between the front of the glaciers and the forests. They developed there because the glacier refrigerated the immediate region around it, and plants could not grow. The lack of plant cover to protect the soil allowed winds to move it. This windblown glacial silt formed the great loess deposits of our central Midwest. It is the lack of plants to protect the soil that is characteristic of all deserts.

In warmer regions the material the wind moves is sand, and it may be formed into sand dunes. The formation of sand dunes and of loess deposits occurs when the wind loses so much kinetic energy that it no longer can carry its load. The shape of sand dunes depends on the strength, constancy, and direction of the wind. Weak winds tend to produce dunes that are transverse, and strong winds produce longitudinal dunes, which are parallel to the direction of the wind. Water is not totally absent from desert areas, but it is very scarce.

REVIEW AND DISCUSSION QUESTIONS

1. Man has tried to save many beaches from the effects of erosion by planting grasses and other plants on the side of the beach away from the ocean. What is the reasoning behind such action?
2. The shape of sand dunes depends to a great extent on the wind. What might be the shape of a sand dune in an area of constantly changing wind direction?
3. Wind generally moves faster than the water in streams. Explain why water erodes better and faster than wind.
4. Compare a cold and a warm desert with respect to vegetation, groundwater, and climatic conditions.
5. A problem in desert travel is locating an oasis. Most oases occur in low spots in the desert and are hidden from view. Explain why this is so.

6. All sand dunes have the same general shape—a gentle slope on the windward side and a much steeper slope on the leeward side. Why?
7. Both central Canada and Arizona get about the same amount of precipitation each year. Canada is mostly forest, muskeg, and tundra, while Arizona is mostly desert. How can you explain this?
8. Many desert animals, such as the spadefoot toad, bury themselves in the sand during long dry spells. This activity, similar to the hibernation of bears, is called *estivation*. How does estivation help desert animals survive?
9. The formation of a stone-paved desert depends mainly on three factors: the plants, the wind, and the rainfall. Explain how these factors influence the formation of this type of desert.
10. How is the erosion of rocks by the wind similar to the cleaning of the face of a building by sandblasting?
11. Pioneers traveling west often found that water in water holes was not fit to drink because of its high mineral content. How did the water get this way?
12. What effect would large numbers of plants growing on a desert have on the desert floor?
13. Explain why trees and other tall plants are not found on the tundra.

CHAPTER 21

WHAT HAPPENS TO THE SEDIMENTS?

We have learned that the debris and ground-up rock produced and carried by a glacier may become part of the load carried by a stream. Flowing water and winds move the products of weathering and erosion from one place to another across the land. This transported material is finally carried to the oceans.

The majority of sediments are dropped where streams slow down as they enter the oceans. We know that the action of ions in salt water helps the finer particles settle and become ooze on the sea bottom far away from the mouths of rivers.

21-1 MOUNTAINS: THE SOURCE OF SEDIMENTS

All of us know that there are hills, mountains, and lowlands on the continents. If we have not actually seen them, we have seen photographs of them. Scientists agree that the highlands are the principal sources of the material that rivers and winds carry to the oceans. How long can erosion continue before the surface of the earth is leveled? Careful studies of the rate at which weathering occurs suggest that the mountains are lowered about 1 foot in 1,000 years. Some mountainous regions are reduced more slowly, and some more rapidly.

The rate at which mountains are eroded must not be confused with the rate at which the whole continent is being washed into the oceans. Not all the material weathered and eroded from the mountains is carried directly to the oceans. Some of it is deposited on the land and later picked up by running water and carried nearer to the oceans. This happens many times before the debris actually leaves the continent. The accepted estimate of the rate at which the continents (not just the mountains) are being reduced and carried to the oceans is about 1 foot of elevation in 9,000 years.

The Nile carries sediments to its delta from the heart of the African continent.

The highest mountains in the United States, other than in Alaska, are between 14,000 and 15,000 feet above sea level. If these mountains are being worn away at the rate of 1 foot in 1,000 years, how long will they last? It would take about 15 million years of weathering and stream action to wear the mountains down to just above sea level.

Fifteen million years is a very long time to us, but not to the earth. Remember, most geologists think the earth is at least 5 billion years old. That is enough time to wear down more than three hundred 15,000-foot mountains piled one on top of the other! At that rate we should have no mountains or even hills on the earth today. Something is wrong with our thinking somewhere.

21-2 DO MOUNTAINS GROW?

It seems we have assumed that the only time mountains could have been formed was when the earth itself was formed. If all mountains had been built at that time, there should not be any mountains today. Since there are mountains today, we must find a way to account for them. Perhaps mountains have been formed at several different times in the past. Perhaps somewhere on the earth there have always been mountains that were growing. And perhaps today there are mountains that are still growing.

Figure 21-1 The Green Mountains of Vermont are examples of mature mountains worn down by glaciation, weathering, and running water. The Tetons of Wyoming are young mountains (see Chapter 27).

Figure 21-2 The Pikes Peak region of Colorado is made up of forests, grasslands, and bare rock. Each of these surfaces is eroded at a different rate. What other factor changes the rate of erosion?

To solve these problems, there are several other questions that must be answered. What happens to all the debris that was once the solid rock of the earth's surface? How much is there of this finely divided material?

21-3 MOUNTAINS LOSE WEIGHT EACH YEAR

Pikes Peak, a 14,000-foot mountain in Colorado, is being worn away at the rate of about 1 foot in 1,000 years. It is difficult to say just how large an area Pikes Peak occupies, because it is part of a group of mountains. This group of mountains covers about 400 square miles. All the rock of the area is granite, so we can assume that it all erodes at about the same rate.

It is very difficult to estimate how much material is being eroded from this region. We must first determine how weathering and erosion of all kinds affect the area. The area is partly covered by forests and grasslands, while bare rock is exposed in some parts, as shown in Figure 21-2. The kind of plant cover affects the rates at which weathering and erosion take place.

To discover precisely what weight of the Pikes Peak region is eroded each year, we would have to study many different sample areas within the region. For each of these areas we would have to measure the results of weathering and erosion. If the job were done carefully and all the different kinds of areas satisfactorily measured, we could estimate an answer to our question.

It took many years of work to arrive at a really good estimate, but one has been made. Geologists think that about 2.2×10^6 tons of material are removed each 1,000 years. This is a rate of about 2,200 tons a year from an area of 400 square miles, or 5.5 tons from each square mile. This represents only 0.06 ounce per square yard per year.

Could we use these figures to help us estimate how much of North America is eroded in a year? We could if we make two assumptions: (1) All of North America is made of the same kinds of rock that are in the Pikes Peak region. (2) The rate of erosion is the same all over the continent.

Is this true? Of course not! The Pikes Peak region is composed of granite, and relatively little of the continent has granite as the surface bedrock. Pikes Peak is a steep mountain with fast-flowing streams in its valleys, whereas much of the continent has a very gentle slope with slow, meandering streams. Even if the results of weathering and runoff were the same throughout the continent, we could not use the Pikes Peak calculations. However, one thing that those calculations do tell us is important: In any mountain region the weight of the mountains grows less every year.

Study Guide

1. What forces act to wear away the continents?
2. Where do most of the sediments come from?
3. Explain what happens to sediments.
4. Explain why all mountains are not eroded at the same rate.
5. Describe how one can arrive at an average erosion rate.

21-4 WHERE IS THE DEBRIS TAKEN?

The material that is removed from the mountains must go somewhere. If the mountains are losing weight every year, some places on the earth must be gaining weight every year.

We know that some of the load the streams carry away from the mountains is deposited wherever the streams slow down. This may be where the streams emerge from steep valleys in the mountains and enter upon more gently sloping plains.

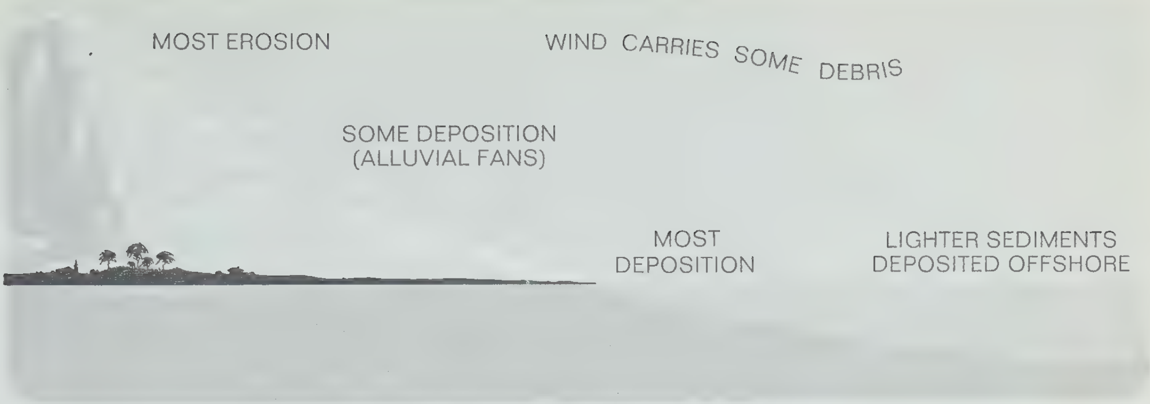


Figure 21-3 The distribution of sediments as they come off the continent

Some of this debris carried by the streams is left on the floodplains during spring floods. In time, this debris will be washed into the stream again by runoff from rain. We also know that the material the streams carry is finally deposited on the ocean floor near the land (see Figure 21-3).

We have seen that the ground-up rock moved by glaciers also gets into streams, and it, too, ends up on the ocean floor. Dust and sand picked up by winds may or may not find their way to the oceans. To get into the oceans, particles must be blown there, or be blown into an area drained by streams that flow into the oceans. For example, a Swedish expedition has found evidence that at least some dust from the dry Sahara reaches the Atlantic Ocean. They found, on the sea bottom between South America and Africa, microscopic stony skeletons of freshwater diatoms known to have lived in extinct lakes of the Sahara (see Figure 21-4).

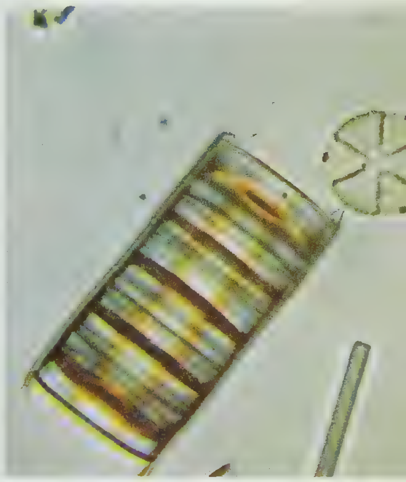


Figure 21-4 Diatoms, a kind of algae, were probably picked up by the wind over the Sahara and dropped in the Atlantic Ocean.

Many tons of rock are being removed from the mountains of North America each year. Ultimately, most of this debris reaches the oceans, where it is deposited on the sea bottom near the shore. What does this do to the earth as a whole? If equal masses are placed on the pans of a balance, the instrument is balanced. When a mass is transferred from one pan to the other, what happens? One pan rises and the other sinks; the instrument is no longer balanced.

We saw in Section 19-5 how the weight of the continental glaciers depressed the land beneath them. Land at some distance from the glaciers had to rise. This adjustment of the elevation of the earth's crust to uneven loading is called **isostasy**. Let us examine the theory of isostasy more closely.

isostasy (eye SOS tuh see); Greek: *isos*, equal + *stasia*, condition of standing.

21-5 THE THEORY OF ISOSTASY

The theory of isostasy requires us to make an important assumption. We must *assume* that beneath the crust of the earth there is rock under enough pressure to be somewhat plastic. The crust "floats" on this plastic rock because the density of the crust is less than that of the rock beneath it.

From observing blocks of wood or anything else floating in water, we know that some part of a floating object sinks into the water. The depth to which the floating object sinks depends upon its density and thickness. We can easily test this by floating various blocks of wood in water. From such observations we can *assume* that the mountains, or "thick" regions of the earth's crust, must extend more deeply into the plastic subcrust than do regions of lower elevation, as illustrated in Figure 21-5.

Imagine several different-sized blocks of the same kind of wood floating in water. Each block will float with a different amount of its thickness above and below the water. But the ratio of the above and below portions of all the blocks is the same.

We can assume that the same thing is true of mountainous areas composed of rocks of the same density. Therefore, what should happen when a mountainous region loses weight through erosion? Why should it rise a little? What should happen to the sea bottom that receives the material removed from the mountains? It should sink a little more deeply into the plastic subcrust because of the increased weight of the debris.

There is a second idea that is included in isostasy. It is the one we explained in relation to the continental glaciers. The plastic rock beneath the outer crust of the earth is confined

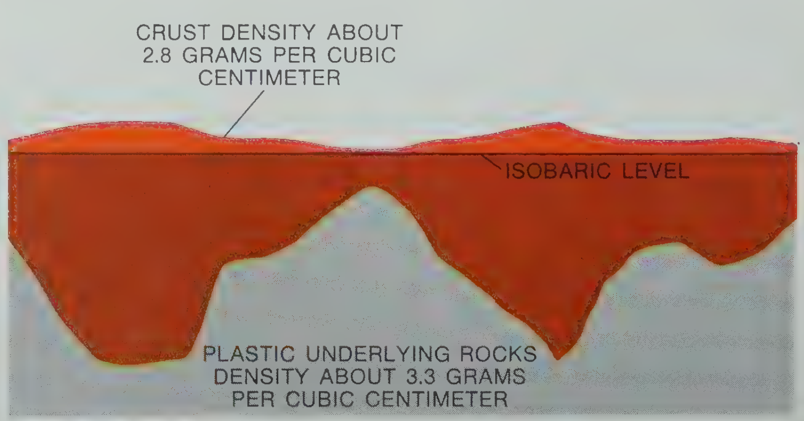


Figure 21-5 Mountains float on the earth's plastic subcrust in much the same way that a piece of wood floats in water.

between the outer crust and the material below. It behaves somewhat like a sealed plastic bag filled with water. If one part of the bag is depressed, other parts of it rise. Why? Water flows from the area under pressure into areas where only the atmosphere is pressing on the bag. It flows from a region of greater pressure to a region of lesser pressure. This happens because the water is in a confined space, just like the plastic rock of the subcrust.

How can we apply this knowledge to the earth? The weight of sediments that accumulate on the sea bottom at the margins of a continent increases the pressure upon the plastic layer of rock far below them. It slowly squeezes a little of the rock out from underneath the area of pressure. Since the earth's crust is somewhat flexible, surrounding areas where the pressure is not so great will tend to rise. Where are there areas of reduced pressure on the earth? There are areas of reduced pressure wherever mountains are being eroded. Why?

There seems to be a continuous, slow movement of the earth's crust. This movement is the way the earth adjusts to erosion (the loss of weight resting on its surface) and to deposition (the increase in weight resting on its surface). The action takes place very slowly because the thick plastic subcrust responds to changes in pressure very slowly—quite unlike the speed with which water responds.

Study Guide

1. How does the weight of the land vary from year to year and place to place?
2. Explain how sediments are distributed.
3. Describe two assumptions in the theory of isostasy.
4. Which extends deeper into the subcrust, plains or mountains? Why?
5. What happens when the density of any floating object is reduced?

21-6 ISOSTASY IN ACTION

Where can we go to discover whether isostasy actually occurs? The best place for such exploration is the underwater margin of a continent, called the **continental shelf**. The continental shelf slopes gently away from the shore (see Section 25-2).

The sediments deposited in the oceans by rivers are distributed over the continental shelf by the combined action of

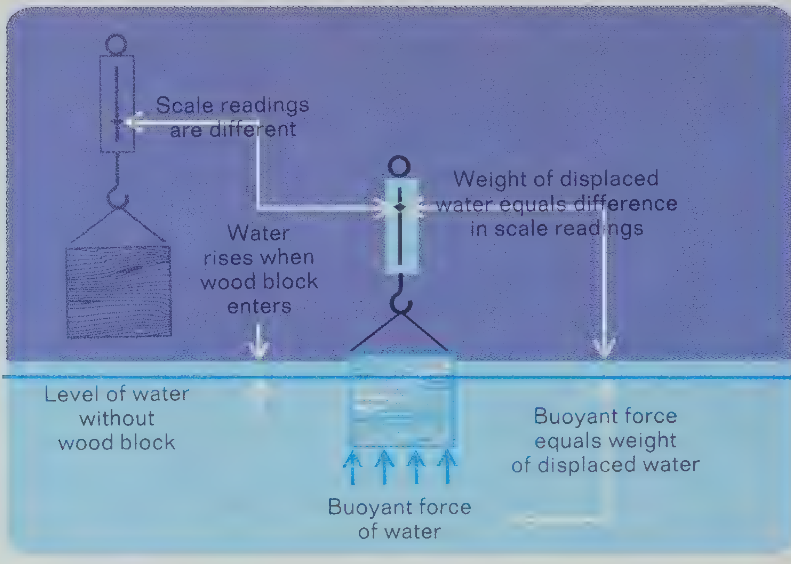


Figure 21-6 The buoyancy of a liquid reduces the weight of a submerged object.

waves and ocean currents. As you will learn in a later chapter, the movements of the sea are slow. They spread the debris from the land in a series of thin, almost horizontal layers. The particles of the sediments have about the same density that the rocks of the continent have. Therefore, you might believe equal volumes of the sediments and of the rocks from which they were made would press upon the earth's crust with equal weight. This is not true. The sediments on the continental shelf press with less weight. Why is this so?

The loose sediments in the oceans are waterlogged. Every particle is surrounded by water. What effect has this upon the weight of the particle? Recall that in determining the density of an object we make use of the fact that buoyancy reduces the weight of a submerged object (see Figure 21-6). The amount of weight that appears to be lost is equal to the weight of the displaced water. Thus, loose sediments in the ocean press upon the earth's crust less than does an equal volume of rock on land.

Another fact must be taken into consideration in thinking about the effects of erosion, marine deposition, and isostasy. The sedimentary material is derived from the surface of the entire continent and is deposited over the entire underwater continental shelf, as illustrated in Figure 21-7. But the area of the continental shelf is only a small percentage of the area of the continent.

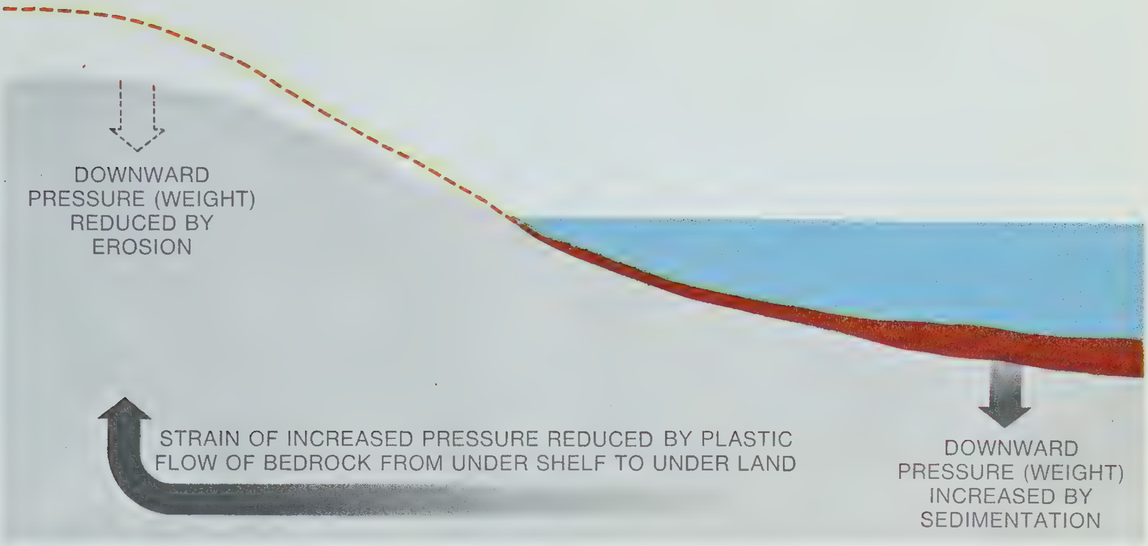


Figure 21-7 The distribution of sediments on the continental shelf has an effect on the sinking of the shelf and the rising of the land.

The sediments on the shelf build up more rapidly than the land wears down. This effect more than compensates for the sediments' apparent loss of weight due to buoyancy. As a result of pressure, the underwater margins of the continents are slowly sinking. Isostasy causes the land of the continents to rise, but not so rapidly as the continental shelf sinks.

21-7 DO MARINE SEDIMENTS REMAIN AT THE BOTTOM OF THE OCEAN?

Thus far, our theory suggests that the ocean bottom is always sinking and the land always rising. Is this supported by evidence? What do we know about marine sediments? We have an abundance of evidence in the form of sedimentary rocks that contain marine fossils. These are found in many places on the land—even on the tops of high mountains. From this we know that marine deposits can be raised high above the level of the oceans.

For other evidence, let us examine the region of the oldest crystalline rocks in North America. Such an area is called a **shield**. Crystalline rocks that are more than 2.5 billion years old have been found in southeastern Canada. The crystalline rocks of the Canadian Shield are surrounded by metamorphosed sedimentary rocks. These in turn are surrounded by

Figure 21-8 Barren land is a common feature of the Canadian Shield.

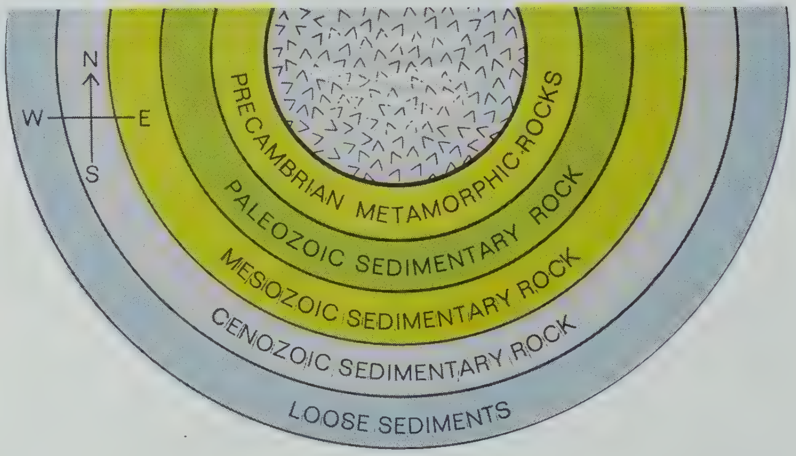


Figure 21-9 The deposits of sedimentary and metamorphic rocks around the Canadian Shield

sedimentary rocks, as shown in Figure 21-9. The ages of these deposits have been estimated from radioactive elements and from the marine fossils they contain.

Farther away from the Canadian Shield, the sedimentary rocks represent younger deposits. Apparently, a large part of North America grew from a small, very ancient landmass of the Canadian Shield. How do you explain this growth?

21-8 HOW A CONTINENT MAY GROW

One way to explain the growth of at least the eastern part of North America is by the growth of its continental shelf. As the land was eroded away, the sediments on the shelf increased in thickness and were spread farther out into the

ocean. In time, the forces of isostasy were so great that the land rose and the outer portion of the shelf sank. The rising land carried up with it those parts of the continental shelf nearest the old land. This increased the area of land.

Another cycle of erosion placed more sediments on the extended continental shelf. Figure 21-10 shows how this happens. Again the shelf grew oceanward. Again isostasy lifted the land and inner portion of the shelf, and the continent grew some more. This kind of action was repeated many times. Very slowly, over more than 2 billion years, North America reached its present size.

Such an explanation of the growth of a continent is in keeping with what we know about the distribution of marine sediments. It involves repeated cycles of erosion and uplift. The material that is eroded becomes continental shelf, only to be raised and form land again at a later time.

The theory of isostasy explains why uplifts occur and a continent grows. Does this theory explain all we know about uplifts and the growth of continents? No, it does not. In later chapters you will see how other forces are involved in raising mountains, some of which were originally ocean floor and therefore are now composed of marine sediments.

We do not know the importance of each of the several forces involved in raising mountains. We are confident, however, that isostasy plays a significant role.

21-9 THE MIDWEST AND THE GREAT PLAINS

The great middle portion of the United States and Canada was formerly sea bottom. Toward the end of the Mesozoic

Figure 21-10 The growth of the continental shelf can be called growth by addition; that is, sediments eroded from the land build up the shelf, which may eventually become dry land.

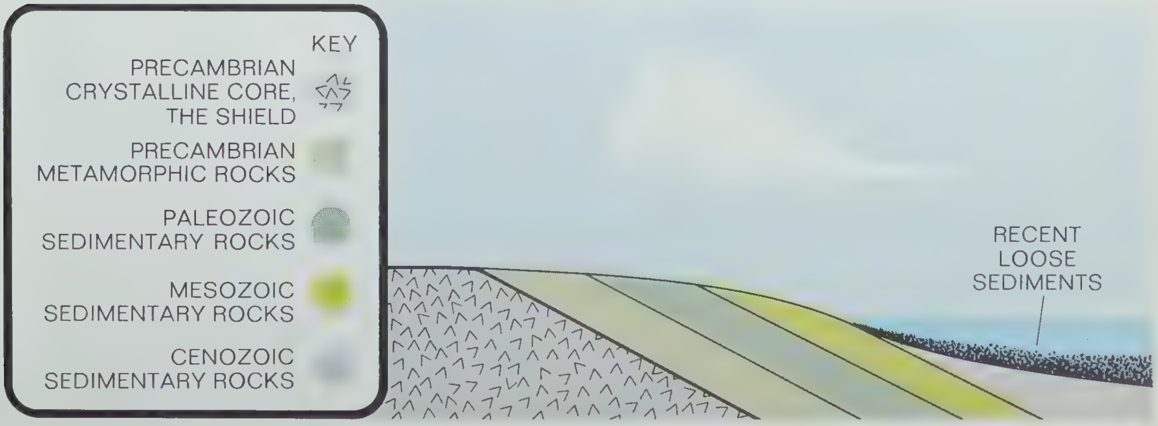


Figure 21-11 The extent of the sea in Canada and the midwestern United States during the Early Cretaceous Period

Era the sea still occupied much of this region, as shown in Figure 21-11. This probably was a shallow sea, not deep ocean. From fossil evidence we know that the thousands of feet of sediments that accumulated were in shallow water. Their weight forced the sea bottom down, allowing deep layers of sediments to accumulate.

A widespread change of the earth's crust seems to have occurred as the Cenozoic Era began. The crust beneath central Canada and our Midwest slowly rose and dried up. The region became a gently sloping, almost level coastal plain (see Figure 21-12). During the 70 or more million years since this newly emerged land was exposed, many surface changes have occurred.

As the new continental shelf slowly rose and was exposed above sea level, water drained off in streams. The streams joined one another and stream systems developed. Slowly the streams removed exposed sediments and carried them back into the sea. When the loose sediments had been removed, the streams attacked and eroded the rock that had been formed from deeply buried sediments on the shelf. By the close of the Tertiary Period most of the major stream systems we know today had developed. They carried to the sea not only material from the exposed sedimentary deposits, but

Figure 21-12 The extent of the sea in Canada and the midwestern United States during the Late Cretaceous Period

Figure 21-13 Canada and midwestern United States as they are today

also material eroded from the newly elevated Rocky Mountain system. All this was ultimately deposited on the growing continental shelf of the Gulf of Mexico.

Throughout this long period, more than 50 million years, the Midwest was greatly changed by streams. Now it can no longer be called a coastal plain, except in the most southern portion. It is still a plain, a land with gentle slope and in many places almost flat. The streams have cut very shallow but broad valleys in it. We call it the interior plain.

The northern parts of the region have been modified by continental glaciers as well as by streams. As you will recall, glaciers covered most of the land north of the Missouri and Ohio rivers. Glacial till covers the surface there. In many places it has buried the work of ancient streams that had flowed across the land. Hundreds of square miles of the once glaciated region are almost flat and are glacial plains. These are superimposed upon the earlier, stream-formed interior plain.

Study Guide

1. Where are the continental shelves?
2. Explain why isostasy occurs along the margin of continents?
3. How old are the rocks in the Canadian Shield?
4. As you move away from the Canadian Shield, what kind of rocks do you find?
5. Where are the youngest rocks in Figure 21-12?
6. At one time, what was the area that is now the Midwest?

SUMMARY

The sediments brought to the oceans by streams and other runoff are spread on the continental shelf. This is an underwater part of the continent that is continuous with the coastal regions of the land. As sediments accumulate, they add weight to the crust of the earth and depress it. The areas that are loaded with sediments sink a little. The eroded land areas rise a little. This balancing is explained by the principle of isostasy.

The loose sediments slowly become sedimentary rocks in which the remains of marine animals may be trapped. All the rocks that contain marine fossils were formed under the oceans and on the continental shelves. We do not know precisely how such rocks were raised to become parts of the land. Isostasy explains part of the action but by no means all of it.

The central part of North America from the Gulf of Mexico well into Canada is underlain with marine sedimentary rocks. This part of the continent grew by the addition of uplifted marine sediments

at its margins. Except along the Gulf of Mexico, the original coastal plain has been changed to an interior plain. This change in character was brought about as streams affected the ancient coastal plain and developed the Mississippi River system and the rivers of Texas. In the northern half of the continent, the Pleistocene glaciers converted many large areas into glacial plains.

REVIEW AND DISCUSSION QUESTIONS

1. Where are the sources of marine sediments and how do the sediments reach the oceans?
2. Why can't the mountains we know today be the original mountains of the earth?
3. Explain how isostasy causes some mountains to grow.
4. Pikes Peak appears to be eroding away at the rate of 1 foot in 1,000 years. North America as a whole is eroding away at the rate of 1 foot in about 9,000 years. Why are these statements not contradictory?
5. Sediments are carried by streams. Why does the water of a little mountain brook reach the ocean much more rapidly than the sediments it picked up?
6. Why would isostasy not operate if the earth were absolutely rigid?
7. Why does loose sand on the continental shelf exert less downward pressure than the same amount of sand on the land?
8. What evidence is there that what is now sea bottom may not be sea bottom in the future?
9. In central Michigan the sedimentary rock is about 30,000 feet thick. Is this evidence that the sea there was once that deep? Defend your answer.
10. Why is the great interior plain of the Midwest no longer considered a coastal plain?

CHAPTER 22

WATER IN THE OCEAN

The oceans cover about 71 percent of the earth's surface. They lie in basins between the continents. Geologists believe the ocean basins were larger and shallower in the beginning than they are today. As the continents grew, the ocean basins became smaller and deeper. The water that fills them came from several sources. Some of it came from the atmosphere, and much of it came from the rocks of the earth's crust. Other water now in the oceans probably came from very deep within the earth.

The deepest parts of the oceans are farther below sea level than the highest mountains are above sea level. The average depth of the oceans is about 3.7 kilometers (2.3 miles), whereas the average height of the continents is barely 0.8 kilometer (0.5 mile).

The careful study of the oceans is a young science. It dates from the 1850's, when Matthew Maury of the United States Navy began to compile sailing charts from the information that had been gathered over centuries. This information consisted of records of water depth, winds, currents, and tides. The next great step forward was a survey of physical, chemical, and biological properties of the oceans. This research was undertaken from 1872 to 1876 by the scientists aboard a British vessel, H.M.S. *Challenger*, on an expedition around the globe.

22-1 SALT WATER

In your study of the water cycle, you learned that the ocean is the reservoir of the earth's water. In Chapter 8, you learned that Joly used the amount of salt in the ocean to estimate its age. We cannot drink ocean water nor can we use it to irrigate our crops, because it is too salty.

Instruments are used to measure the velocity and direction of deep currents.

Figure 22-1 Rivers carry sediments and dissolved salts to the ocean. Why are some lakes salty and others "fresh"?

Figure 22-2 In 1,000 grams of seawater there are 35 grams of salt and 965 grams of water. Salinity is designated as o/oo (parts per thousand).

You know that fresh water on the land comes from rain and snow, which in turn come from evaporated ocean water. Only a minute amount of salt leaves the oceans and enters the atmosphere. When water evaporates, it leaves behind the salts that were dissolved in it. However, land water is not completely pure—it has some salts in it. These salts are produced by weathering of rock and soil. If you taste the "fresh" water from the Mississippi River, it will not taste salty. Furthermore, you can irrigate crops with it. But dissolved in this Mississippi water are the salts from an area of land equal to about 1.4 million square miles. This amounts to about 137 million tons a year.

The saltiness, or salinity, of seawater depends on the amount of dissolved materials in it. **Salinity** is measured as the weight of dissolved salts in 1,000 grams of water. The average salinity of seawater is about 35 grams per 1,000 grams of seawater (see Figure 22-2). Scientists do not know whether this average is changing; their records are not old enough to show a change over the years. Why might you believe the salinity is increasing? Eighty-five percent of the dissolved particles are sodium and chlorine ions. When these combine, they produce sodium chloride, or table salt. That is why the ocean tastes salty. It is interesting that this percentage of 85 never varies. For thousands of years, man has evaporated seawater for its sodium chloride.

The crust of the earth is the source of the many kinds of ions found in the ocean. There are 215 times as many sodium

atoms as chlorine atoms in the earth's crust. In spite of this, river water contains only about $1\frac{1}{2}$ sodium ions for each chlorine ion. In ocean water there are about equal numbers of sodium and chlorine ions. Why are sodium and chlorine ions such a high percentage of the dissolved salts in seawater? Both sodium ions and chlorine ions rarely combine with the other kinds of ions found in the ocean to produce insoluble substances. Therefore, both elements stay in the water as separate ions.

Most of the sodium in the crust is found in minerals that do not weather readily. Chlorine, however, is found in minerals that are usually soluble in water. That is why ocean water contains about equal numbers of chlorine and sodium ions.

Recall that Joly tried to estimate the age of the ocean from the sodium and chlorine it contains. These ions have been accumulating ever since oceans came into existence. Over this period the ions have diffused (scattered) through the water, so that now they are almost uniformly distributed.

Slight differences in salinity do occur. For instance, the surface water of the Atlantic Ocean has a salinity of about 36.0 parts per thousand, whereas the bottom water has about 34.8 parts per thousand. In confined seas, the salinity may vary from that of the open oceans. In the Red Sea the water is saltier than usual, whereas in the Baltic Sea it is fresher. Locate these seas on a map and see whether you can discover why their salinity differs from that of the open oceans. In Section 22-9 you will learn how differences in salinity cause a current.

Figure 22-3 shows that there is a very small change in surface salinity from north to south. Such a change is due to the difference in evaporation and precipitation. Which process would increase the salinity?

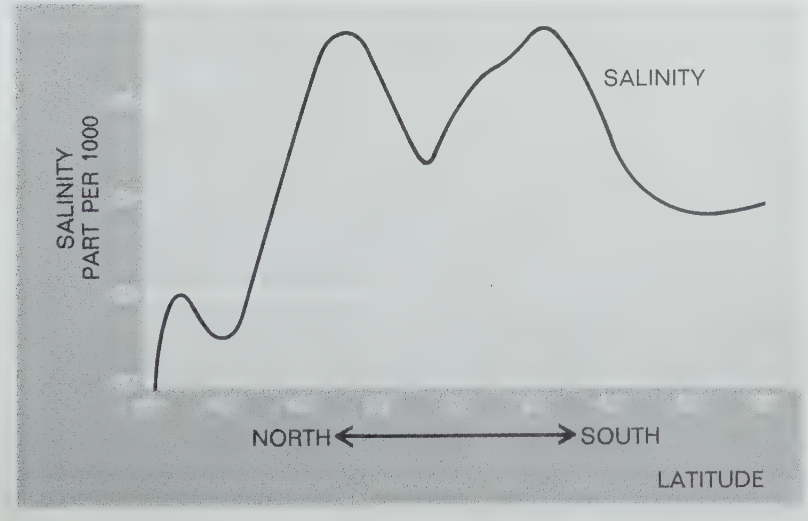


Figure 22-3 The surface salinity of seawater varies with latitude. Why is the salinity great at 30°N?

Figure 22-4 Open Nansen bottles are attached to a weighted cable and lowered overboard. If a closed bottle filled with air is lowered, the pressure of the water at depth will crush the bottle, like the one seen in this photograph.

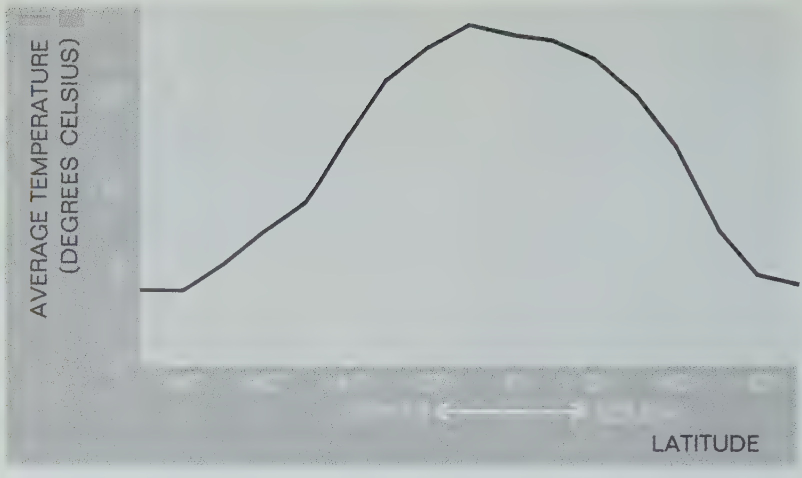


Figure 22-5 The average temperature of seawater with latitude. Why is there a variation of temperature with latitude?

The effect of evaporation and precipitation is only "skin deep." We have learned this by collecting water at many depths below the surface. Samples of seawater are brought up in a series of Nansen reversing bottles (see Figure 22-4). The open bottles are lowered on a wire. At the desired depth, a spring catch is released by a free-falling weight attached to the wire. In this way, the bottles are closed, trapping water at the desired depth. There are also electronic devices to produce a continuous salinity-versus-depth record.

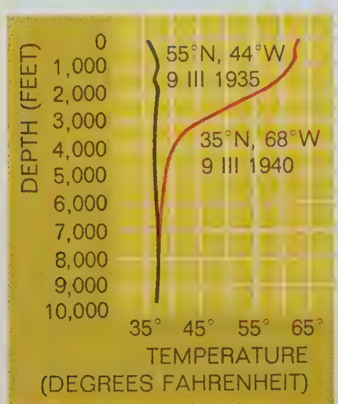


Figure 22-6 Temperature-depth curves

22-2 TEMPERATURES OF OCEAN WATER

At the surface, water is warmed or cooled. In the equatorial region the input of solar energy and its conversion to heat is high. In the high latitudes the input of solar energy is low. Therefore, surface temperatures of seawater vary from the equator to the poles. Figure 22-5 shows this variation. As you will learn later, ocean currents distribute warm, equatorial surface water to the colder regions. This is one of the reasons why the higher latitudes do not become colder and colder.

With few exceptions, water temperatures decrease with depth. The vertical temperature patterns differ, depending on the latitude. Figure 22-6 shows temperature-depth curves for two latitudes. Notice how different these patterns are. The temperature pattern for a higher latitude shows that the temperature is about the same from top to bottom. The other curve shows an area where temperature changes rapidly with

depth. How does the wind influence such a temperature-depth curve?

Temperature measurements below the surface are made by attaching a shielded minimum thermometer to a Nansen bottle. As the bottle is raised, the mercury of the thermometer does not move even though the thermometer passes through warmer water. Another type of instrument is the **bathythermograph**, which produces a continuous temperature-depth record (see Figure 22-7).

A Nansen bottle holds a shielded thermometer, which records the temperature of water at a certain depth. This bottle also carries an unshielded thermometer, which also records the temperature but whose mercury is affected by the pressure of the water. In this way the depth of the bottle is calculated.

22-3 OCEAN CURRENTS

Both the atmosphere and the oceans are fluid, and they both have horizontal and vertical currents. Sailors have measured and recorded currents and winds for hundreds of years. In the shipping lanes, where traffic is heavy, currents were accurately mapped because they were observed so frequently. In the areas that were seldom traveled, which include most of the ocean, there was not enough information to chart currents with any degree of accuracy.

Look at a modern globe or world map, or better still, a specialized chart for ocean navigation. You will see nicely drawn, sweeping arrows that are supposed to indicate currents. In a general sense, they do indicate that a current was found there at one time. But think of where you live. Does the wind always blow from the same direction at the same speed? Of course not.

How unrealistic a weather map would be if each observation were made on a different day or even month! This does not happen because there is a network of weather stations that make observations at set times.

Figure 22-7 A bathythermograph contains a temperature- and a depth-recording device. The temperature-depth record is scratched on a smoked-glass slide, which is inserted into the bathythermograph before lowering.

There is no such network of stations making current observations in the oceans. Moreover, the sailors and oceanographers who have been measuring and mapping currents have found this to be a very difficult task. It is difficult because the ocean is so large and because measuring currents is time-consuming, expensive, and very uncertain.

Think of the problem of measuring a current from a ship moving along with the current. Unless you are within sight of land, you have no direct method of measuring your speed or direction. However, a radio navigational aid called *loran* does help in locating the position of a ship. If the position of a drifting ship is determined every hour, then the speed and direction of the current can be determined. Of course, the wind will influence the drift of the ship. You can see that there are many problems in making current measurements.

loran; from LOng RAnge Navigation.

Figure 22-8 The system of ocean surface currents

After you have studied the chart of the ocean circulation, Figure 22-8, you might wonder why currents exist. You might also wonder why they are located where they are. What makes water move? Let us try to understand the forces acting on water to make it move.

22-4 GRAVITY AND DENSITY

Gravity will move water. But gravity by itself would not create an ocean circulation. However, combined with the sun's energy, gravity is a strong mover of water. You have already learned that some of the sun's energy heats ocean water.

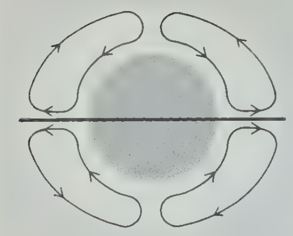


Figure 22-9 A model of the ocean currents that are caused by heating at the equator and cooling near the poles

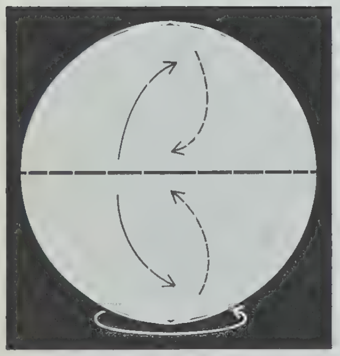


Figure 22-10 The Coriolis effect on the ocean circulation of Figure 22-9 would deflect the currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The dashed arrows represent deep currents.

Water gains heat in the tropics and loses it in the higher latitudes. If there were no circulation of water and air, the tropics would get hotter and hotter and the higher latitudes would get colder and colder.

In order to see how heating, cooling, and gravity can cause an ocean circulation, let us set up an imaginary model of an ocean that covers the whole globe. For the sake of simplicity, we shall also imagine that there are no winds and that the earth does not rotate. Our tropical ocean is heated at the surface by energy from the sun. Our polar oceans lose heat at the water-air boundary.

Since the tropical water would be warmer than the polar water, it would be less dense. This being the case, it would occupy more space. In order to occupy more space, it would have to expand upward against the atmosphere, which would offer little resistance. In this way, the level of the tropical ocean would become a little higher than the level of the polar oceans. Therefore warm, tropical ocean water would flow downhill toward the polar oceans (see Figure 22-9).

In the same ocean model, cold air absorbs heat from the surface of the polar oceans. The surface water becomes colder and therefore more dense. When that happens, the surface water must sink, because it has become denser than the water below the surface. At some depth below the surface, polar water would flow toward the tropical ocean. At the surface, water would be moving in the opposite direction, as we have already seen.

In our "hot-cold" model of the ocean, a difference in density due to a difference in heating and cooling produces a polar-equatorial circulation. Is this type of circulation anything like the circulation seen in Figure 22-8?

What will happen to the north-south currents in our "hot-cold" ocean model if it is rotating, as, of course, the earth is doing? You have already learned about the Coriolis effect. In both hemispheres, water flowing toward the poles is turned eastward. Water flowing toward the equator is turned westward, as shown in Figure 22-10. Therefore, on our model we would expect to see surface water flowing generally to the east, and deeper water flowing more or less westward. Figure 22-8 does not show a pattern like this, so there must be other factors that produce and guide currents.

Study Guide

1. Where does the salt in ocean water come from?
2. Define *salinity*.

3. In Figure 22-3, which latitudes show water with the *highest* salinity?
4. What is a Nansen reversing bottle?
5. Where does ocean water gain and lose most of its heat?
6. In the "hot-cold" ocean model, in which direction does surface water flow? Why?

22-5 THE FORCE OF WIND

Let us set up another model of the earth, using the global winds—the trade winds and the prevailing westerlies—as the only driving force for water. When a light breeze blows over the ocean, there is very little friction between the air and the water. As the wind increases in velocity, it causes the water surface to ripple. When ripples appear, the wind presses on the side of the ripples and the water starts to move with the wind.

If oil, especially fish oil, is poured on water, it prevents the wind from making ripples, and the water will not be put in motion.

How fast and how deep down the water moves depends on three factors: (1) the speed of the wind, (2) the length of time the wind blows in a certain direction, and (3) the distance of open ocean over which the wind blows. The last factor is known as **fetch**. In general, the speed of the water is only about 2 percent of that of the wind. For this reason, wind-caused currents in the open ocean are not very swift.

Figure 22-11 shows that our "wind" model of the earth has no continents. Therefore, the global winds would form broad, surface ocean currents flowing around the earth. This "wind" model is a little like the pattern seen in Figure 22-8. There is a current in the region of the trade winds and a current in the region of the westerlies. On the actual earth, there is a region where no continent blocks wind or current. The westerlies in the Southern Hemisphere make a circular pattern around the earth. This wind pattern produces a broad, shallow current, called the West Wind Drift, that circles the Antarctic continent.

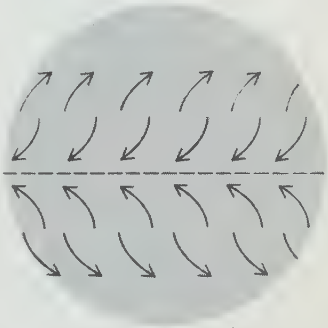


Figure 22-11 A model of the ocean currents that are caused by the effect of winds

Adding the continents to our "wind" ocean model will give us a fairly accurate representation of the major surface currents of the oceans. Look at Figure 22-8 to see what happens to the currents produced by the trade winds. They become the North and South Equatorial currents. In the western margins of most oceans, these currents run into land, which turns them north or south. As they flow north or south along the coast, they are gradually turned eastward by the Coriolis effect. Eventually, the currents reach the latitudes of the westerlies, which drive them eastward. In the Northern Hemi-

sphere these currents are called the North Atlantic Drift and the North Pacific Drift. On the map, you have already discovered the West Wind Drift around Antarctica.

22-6 CURRENTS AND ROTATING SEAS

gyre (JEYE ur).

What happens to the ocean water between the trade winds and the westerlies? These areas have variable, light winds. In the Northern Hemisphere the bodies of water in these areas slowly rotate clockwise. The trade winds push the southern part of the rotating water westward. The westerlies push the northern part eastward. Such rotating water is called a **gyre**. The Sargasso Sea is the gyre in the North Atlantic Ocean.

Sargasso weed floats in the Sargasso Sea in relatively small patches. It does not create a navigational hazard as the myth would have it.

Warm surface water piles up in the gyres because of the Coriolis effect. As the winds drive the water into motion, water slips to the right of the direction of the wind. In this way, water is pushed into the center of the gyres by the trade winds and the westerlies.

As the currents around the gyre flow poleward between the continent and the gyre, they become narrow and deep. Return to Figure 22-8 and locate the Gulf Stream, the Kuroshio, and the Agulhas Current. Notice that these are all on the western side of their respective oceans.

On the eastern side of the oceans, water is generally flowing toward the equator as part of the eastern side of the gyre. Here the currents are very slow, wide, and shallow. Although they are not fast and deep, they do transport a great amount of water because of their large cross section. In Figure 22-8, locate the Canary and the Benguela currents in the eastern side of the Atlantic Ocean. Locate the California and the Peru currents in the Pacific Ocean. These currents are relatively cool, wide, and shallow. They seldom exceed a speed of 1 mile per hour.

22-7 CURRENTS IN REVERSE

You have seen that the patterns of ocean surface currents strongly resemble the patterns of global winds. The surface currents are guided by the Coriolis effect and the location of land barriers. Are there any other types of surface currents?

In Section 12-11 you learned about the area called the doldrums, which is between the northern and southern trade winds. This is the area of the heat equator—just north of the geographical equator. Here air is generally rising, and the

winds are weak and variable. Therefore, there is no force to drive water. In the Atlantic the trade winds pile up water along the northeast coast of South America, making a "hill" of water. The water on the northern slope of this "hill" flows north into the Caribbean. The water on the southern slope flows south and becomes the Brazil Current.

In the area of the doldrums, where there is no prevailing east wind, water flows downhill eastward, back toward Africa. This is known as the Atlantic Equatorial Countercurrent. In the Pacific there is also an equatorial countercurrent, which is even better developed than the one in the Atlantic. In the Indian Ocean there is an equatorial countercurrent, south of the equator, that varies with the monsoon winds.

22-8 THE GULF STREAM

The only great ocean current along the shores of the United States is the Gulf Stream, perhaps the mightiest of all ocean currents. The source for the Gulf Stream is the broad surface of the equatorial Atlantic. We have seen how the trade winds drive the surface waters westward. The northeastern coast of South America guides most of the water of the equatorial currents into the Caribbean Sea. However, even in the Caribbean there is no well-defined, fast-flowing current. Pushed on by the trade winds, the broad, slow surface flow is concentrated and funneled into the straits between Yucatán, Mexico, and the western tip of Cuba. From there it runs into the water of the Gulf of Mexico, which turns the current eastward.

By this time the current is known as the Florida Current, which flows up along the east coast of Florida (see Figure 22-12). The fastest part of the current is usually about 18 miles offshore, where it averages about 3 knots (a little over 3 miles per hour, or 150 centimeters per second). The Straits of Florida are not wholly filled with rushing water. Most of the current is pushed to the western two-thirds of the straits. The curving coastline and bays of northern Florida, Georgia, and the Carolinas are sculptured by eddies from the Gulf Stream.

After the Gulf Stream takes on a northeasterly course east of Cape Hatteras, it does not stay in a fixed path. It meanders like a river. Some of the meandering loops work themselves downstream. Others break off from the main current, forming great detached eddies of water. North and west of the Gulf Stream the coastal water is cold, having come down from between Labrador and Greenland. South and east of the Gulf Stream the water is warm, about 25°C (76°F).

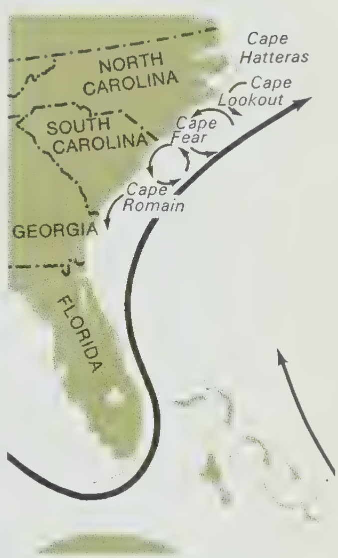


Figure 22-12 The Florida Current becomes the Gulf Stream.

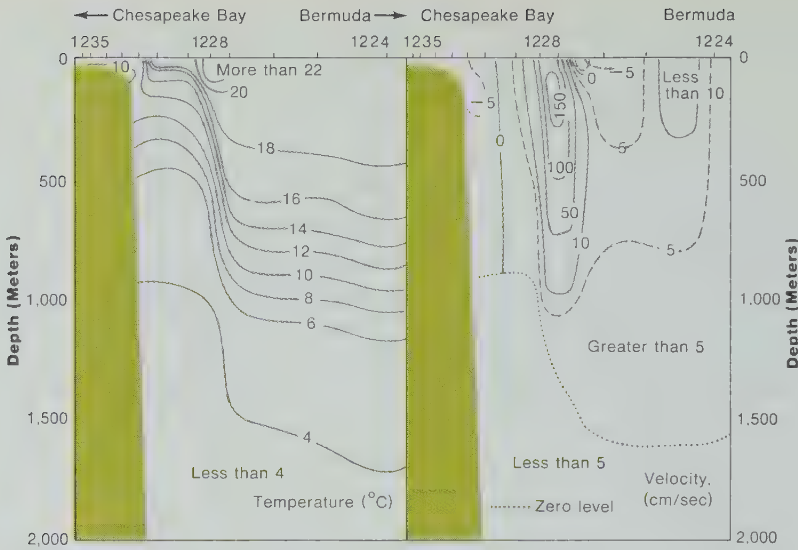
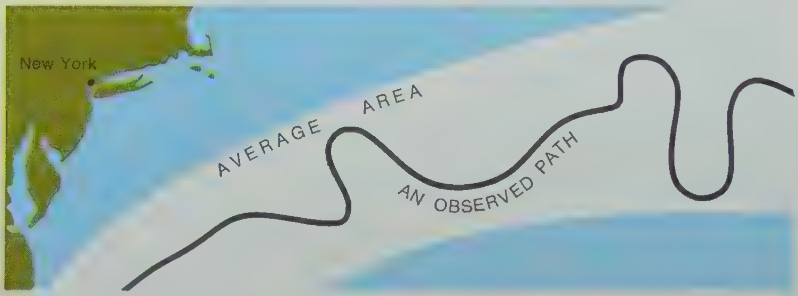


Figure 22-13 Cross section of the Gulf Stream showing (A) temperature and (B) velocity

Figure 22-13 shows the temperature-depth and velocity-depth pattern of the Gulf Stream on a crossing from Chesapeake Bay to Bermuda. Notice the region of greatest temperature change. Is it in the region of greatest velocity? Which side of the current is warmer?

The Gulf Stream is a very intricate flow of warm, tropical water with cold, arctic water flowing southward along its west side. Its pattern is complicated by changing, cold countercurrents, meanders, and branches. It is not possible to drift on the Gulf Stream and get a free ride to Europe. Oceanographers have tried to do this, only to find that they became caught in a countercurrent flowing in the wrong direction. In other cases, they have been carried far north in a branch of

Figure 22-14 The Gulf Stream meanders along its length, forming eddies. Although the Gulf Stream continuously changes its position, it can usually be found within a well-defined area.



the current, or they have been carried in a huge eddy and traveled in a circle.

In the northern part of the North Atlantic Ocean, the Gulf Stream acts as a kind of rim—or even a "dam"— for the Atlantic gyre. It is as though the Gulf Stream keeps warm surface water from bathing the shores of Greenland. The Gulf Stream does, however, carry warm water to the western coast of the British Isles and Norway. Perhaps if this "dam" along the Sargasso Sea were not there, even more warm water would spill over to the European coast.

Study Guide

1. Name the current that circles the earth.
2. What currents are formed by the trade winds?
3. On which side of the oceans are the strongest currents? Why?
4. Name the currents around the gyre in the Atlantic Ocean.
5. In Figure 22-8, locate and name three currents that flow toward the equator.
6. In Figure 22-13, which side of the current is colder?

22-9 SALT, SUN, AND MOISTURE

Earlier in this chapter you learned that currents could be the result of different amounts of energy received by the various parts of the ocean. These differences affect the density of the water. In the "hot-cold" model of the ocean, you saw that currents might be formed by the convection of ocean water. The salinity of water also affects its density. A difference of salinity between two areas will produce a very slow and deep current. Salinity differences are determined by different rates of evaporation and precipitation at the ocean surface. Here again you see the close relationship between the ocean and the atmosphere.

How do you suppose a difference in salinity between two areas occurs? Evaporation of water makes a sea saltier, and heavy rainfall makes a sea less salty.

The Mediterranean Sea connects with the Atlantic Ocean, and the Red Sea connects with the Indian Ocean. Both seas are in arid climates. This means that dry air removes more water from the seas than it gives to them. In fact, the Mediterranean loses an average of 70,000 tons of water a second to the air above it. The salinity of this sea is about 39 parts per thousand, whereas the average salinity of the Atlantic is only about 35 parts per thousand. Why should this difference form a current between these two bodies of water?

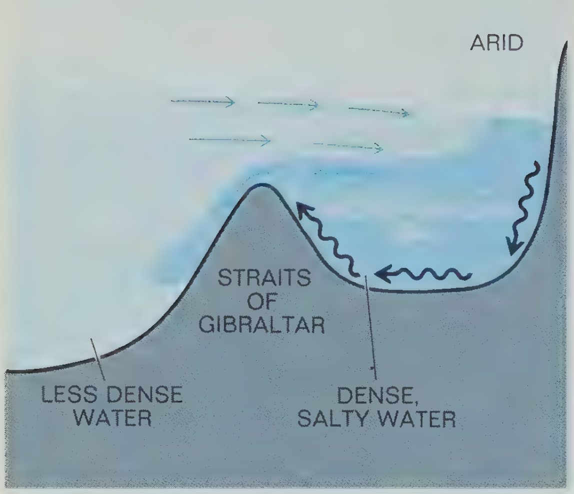


Figure 22-15 The circulation in a sea in an arid climate. Why does Mediterranean water become denser than Atlantic water?

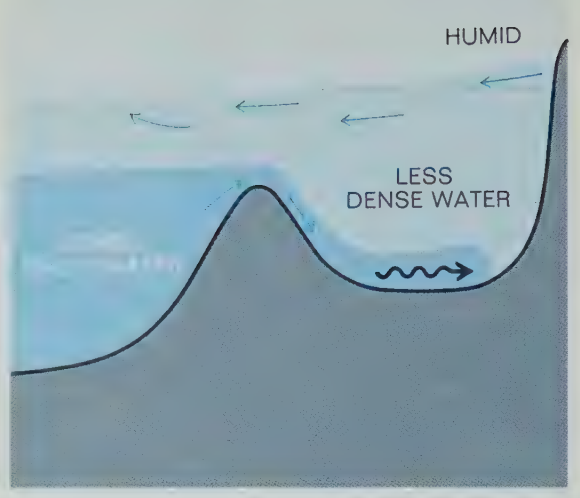


Figure 22-16 The circulation in a sea in a humid climate. Where does the denser water come from in such a sea?

When the dense, salty water is cooled in the winter, especially in the eastern end of the Mediterranean, it becomes even denser and sinks (see Figure 22-15). Since it is denser than Atlantic water, it takes up less space. As a result, the sea level of the Mediterranean becomes slightly lower than that of the Atlantic. Therefore, fresher and less dense surface water from the Atlantic pours through the Straits of Gibraltar into the Mediterranean.

A sill is the raised floor of an entrance to a sea, a fjord, or even a room.

What happens to the heavy Mediterranean water? Salt-heavy Mediterranean water flows close to the bottom, out of the sea, over the Gibraltar sill, and into the Atlantic. There it sinks to the level of its own density. Submarine commanders have made use of these oppositely flowing currents that pass Gibraltar to drift in and out of the Mediterranean with their motors silenced.

What do we know about the deep circulation of seas in regions of heavy rainfall? The Baltic Sea, the Black Sea, and the fjords of Norway are either in areas of heavy rainfall or where they receive much runoff from rivers and glaciers. These basins also have a sill at their entrance (see Figure 22-16). You can see that the surface water in these seas is relatively fresh, from rain and runoff. Therefore, the surface water is less dense than that of the neighboring seas and oceans. This means that the sea level is higher than the level in the

neighboring sea or ocean. Under these conditions, surface water of the Baltic flows into the North Sea. Deep, salt-heavy water flows over the sill from the North Sea into the Baltic.

In Figure 22-16, look at the area above the sill. What might happen if the outflow of fresher water were deeper than the depth of the sill? Perhaps no dense, bottom water could get over the sill into the sea. This is what happens in the Black Sea, with its shallow entrance (40 to 90 meters) through the Bosporous. No new water can creep over the sill and get into the Black Sea. Therefore, the deep water in the Black Sea is never renewed; it is stagnant. Below 50 meters (150 feet) there is no oxygen dissolved in the water. For this reason, higher forms of life cannot live there.

22-10 DEEP CIRCULATION IN THE OCEANS

Oceanographers have measured temperature, salinity, and oxygen content at hundreds of thousands of places in the oceans. At each place, or station as it is called, they collect water samples from several depths, down to the bottom. In order to interpret their measurements, they plot them on charts and graphs.

There are several questions oceanographers have had to answer before their charts and graphs made sense. Why is bottom water almost at freezing temperature? How does oxygen in bottom water get there? Where does water change its salinity?

The characteristics of ocean water are changed at the surface, where it meets the atmosphere. Water becomes cooled or heated at the surface. Where is cold water formed? It must be chilled where the air is cold—in the high latitudes. Where does water get its oxygen? Surface water must get oxygen from the air. It is also at the surface of the ocean that dry air absorbs moisture, making the surface of the water more salty. Again, it is at the surface that rain, snow, and rivers dilute the water, making it fresher.

You have already learned that the density of ocean water depends on its temperature and salinity. The colder the water, the denser it is. The saltier the water, the denser it is, and vice versa. Around Greenland and Antarctica, water is cooled to freezing during the winter. When water freezes, it gives off its dissolved salts. These in turn make the surrounding water saltier and therefore denser. This cold, salt-heavy water that is denser than the water around it slowly sinks and spreads throughout the oceans. Remember that our "hot-cold" ocean model suggested such a circulation.

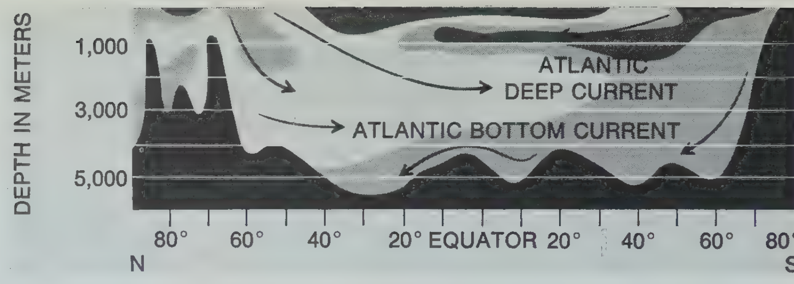


Figure 22-17 The distribution of salinity in the ocean helps to identify the deep, slow currents. Increasing salinity is shown by darker tones.

It has been estimated that the slow convection of this heavy water is only about 20 kilometers per year. (How many centimeters per minute would this be?) Such a movement is far too slow to be detected by current meters of any kind. How else could you detect this very slow movement? Perhaps by putting dye on the surface you could detect a downward movement.

Slow movements such as this may be noticed in a certain type of chart. Figure 22-17 is a chart of salinity measurements in the western Atlantic Ocean basin. The shading represents areas of equal salinity. Notice that these areas make tonguelike patterns. Oceanographers interpret these patterns as representing the circulation of deep water. Now you can understand why the deep water is cold and why it contains oxygen. You have learned that in a few places cold water leaves the surface and moves downward, carrying oxygen with it. In other places water must rise.

22-11 RISING WATER

You have learned how oceanographers have interpreted salinity patterns as movements of water. Surface temperature patterns tell us something else about ocean circulation. In Section 22-2, Figure 22-5 shows average surface temperatures. They are about as you would expect—highest near the equator and lowest near the Poles.

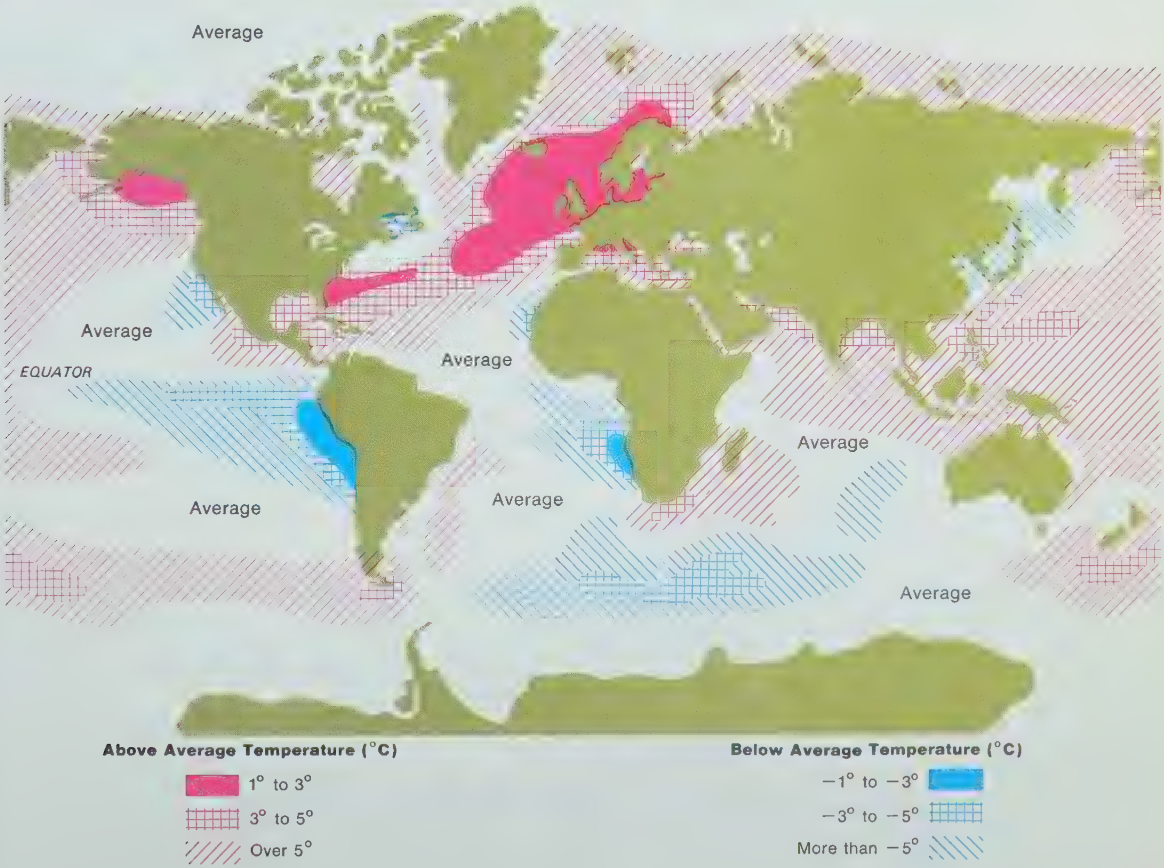
Now that you have seen what average temperatures are, you are ready to understand the chart of above- and below-average surface temperatures (Figure 22-18). Notice the areas of below-average temperature off the west coast of South America and the west coast of Africa. Where is the cold water coming from? In this case, the trade winds blow warm surface water away from the coast. What takes the place of this

water? Cool water from about 200 meters below the surface creeps up along the bottom near the coast. This upward movement of water is called **upwelling**.

Water that has upwelled is cooler than the water it has replaced. Therefore, it appears on the chart as an area of below-average temperature. Upwelling brings up bottom water, which is usually rich in minerals necessary for plant growth. For this reason, these areas are rich in marine life.

Upwelling also occurs off Nova Scotia and China. In this case, the prevailing westerlies drive surface water away from the coast. Cold bottom water rises to take its place. The colder-than-average area off California is also caused by upwelling. There are several other factors involved in this

Figure 22-18 Above- and below-average temperatures of the oceans



upwelling in addition to the offshore winds. The cooler-than-average area between Africa and Antarctica is another area of upwelling. Whalers have come to this area for hundreds of years to catch the Antarctic whale. Why?

What do the areas of above-average temperatures tell you about the circulation of the ocean? They show the warming effect of warm surface currents. Notice how the Gulf Stream warms the northeastern Atlantic.

Study Guide

1. Why are submarine commanders able to drift their vessels either in or out of the Mediterranean?
2. Why is there no oxygen in the waters of the Black Sea below a depth of 50 meters?
3. Where is cold water formed?
4. In Figure 22-17, where is the salinity of the freshest seawater?
5. How do we know where water is upwelling?

SUMMARY

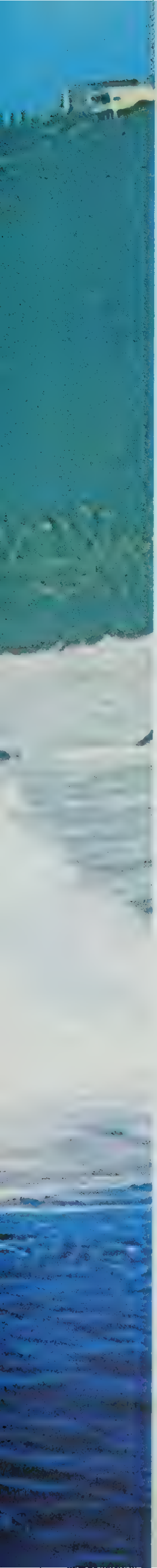
When rainwater flows over the land, it dissolves minerals, especially sodium chloride. These dissolved minerals are carried into the oceans and stay there. It is these dissolved materials that make seawater salty; its average salinity is about 35 parts per thousand. In the open ocean the salinity is always close to this average. Water is made cold and dense at the surface in the high latitudes. Such water sinks in certain locations, forming the deep, cold water of all ocean basins.

There are two main forces that form ocean currents: wind and gravity. The Coriolis effect and the contours of the continents guide the currents. The great surface currents, such as the Gulf Stream, are wind-driven. Deep-water circulation is primarily gravity-density-driven. Upwelling water, usually along a coast, is caused by offshore winds blowing surface water away from the coast.

REVIEW AND DISCUSSION QUESTIONS

1. If 85 percent of the dissolved salts in ocean water are sodium and chlorine ions, determine the weight of these ions in a kilogram of water.
2. How much salt can water contain before it is termed undrinkable? Use a reference book.
3. From Figure 22-3 at what latitudes is there the greatest evaporation going on?
4. List three factors that determine the salinity of surface water.
5. Explain why Nansen bottles are submerged in the open position rather than in the closed position.

6. Study Figure 22-6 and explain why the two curves are so different.
7. How great are the temperature gradients between 1,000 feet and 3,000 feet in Figure 22-6?
8. Why is it difficult to measure ocean currents?
9. Explain why Figure 22-10 differs from Figure 22-9.
10. The temperature-depth curve of Figure 22-6(b) is from a gyre. Tell why the water of the upper 1,500 feet is all the same temperature.
11. Compare the currents in the western parts of the oceans with those in the eastern parts.
12. Explain why there are equatorial countercurrents.
13. Where does the energy and the water for the Gulf Stream come from?
14. In Figure 22-13, locate the area of greatest temperature change at the surface. Between which two stations does it occur?
15. In Figure 22-13, which side of the current is warmer? Which side is slightly higher? In which direction is the water flowing —into the page or out of the page?
16. In which direction does bottom water flow at the entrance of a fjord? Explain your answer.
17. From Figure 22-17, tell where the two main sources of bottom water are formed.
18. Why is all deep ocean water close to freezing?
19. In the lower latitudes, on which side of a continent does upwelling occur?



CHAPTER 23

WHY ARE THERE WAVES?

All of us have looked at an ocean, a lake, or a pond and noticed that the surface of the water is rarely still. It is usually disturbed by waves. They may be tiny ripples that lap gently at the shore of a pond or giant breakers that crash on the ocean shores. What are these waves? How are they different from each other? What causes them to form? These are questions that we must answer before we can explain the effects of the sea on the land.

23-1 MOVEMENT THROUGH MATTER

What does the word *wave* mean? You see your friend across the school grounds, and you wave to him. The flag on a flagpole waves in the breeze. During a parade, waves of marchers pass the reviewing stand. In Section 12-3 you learned about the waves of solar radiation. And, of course, you see waves on water. There is the idea of motion in every use of the word *wave*.

Waves involve movement, and movement involves energy. Therefore, we must ask physicists, who study energy, for the definition of a wave. They define a wave as a disturbance or vibration that moves progressively through a medium. Notice that the definition does not mention energy. Energy causes the wave, and energy is carried by the wave, but it is not a part of the wave.

Study the definition word by word. When waves move across water, what is the disturbance? The originally calm, level surface of the water is changed to a surface that moves up and down (see Figure 23-1). The up-and-down movement is the disturbance. The fact that we can see a wave move across the water shows that it is moving progressively. The medium is the water. Thus, water waves fulfill the physicists' definition of a wave.

Waves are the effects of wind on water.

Figure 23-1 Ripples are caused by wind or by some other factor that disturbs a water surface.

23-2 DESCRIBING WAVES

Anyone who has watched a lake or the ocean day after day knows that waves vary in size. How do physicists describe and measure waves? They use three measurements: wavelength, wave height, and wave frequency.

Figure 23-2 shows that the high points of a wave are called **crests** and the low points are called **troughs**. The distance from one crest to the next is the wavelength. The vertical distance from the top of the crest to the bottom of the trough is the **wave height**.

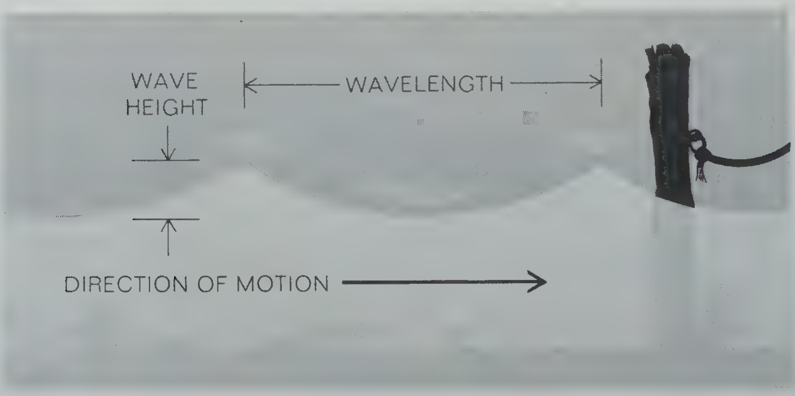


Figure 23-2 The parts of a wave

Figure 23-3 You can shake a Slinky or a piece of rope to form a shear wave.

Figure 23-4 Pressure wave in a stretched Slinky

The number of waves that pass a fixed point in a second is called the **frequency**—five per second, for example. Wave frequency can be expressed in another way. This is the **wave period**, the time it takes for one complete wave to pass a fixed point such as a piling. The wave period is usually measured in seconds. If you know the wavelength and the wave period, how can you determine the speed of the wave?

23-3 KINDS OF WAVES

Imagine two people holding a rope stretched between them. One jerks the rope to the left and right, or up and down, and you see a wave travel along the rope, as in Figure 23-3. We could call such a wave a **shake wave**. The physicists' name for it is a **shear wave**.

Remember that both *shake* and *shear* begin with *sh*.

Can we produce waves by another method? Slightly stretch a spiral spring on the floor, as in Figure 23-4. The toy called a Slinky is just right for this demonstration. Compress, or squeeze together, about a foot of the extended spring somewhere near the middle. Then quickly let go of the compressed section. What happens? You see a wave of compressed loops travel the length of the spring and return. Physicists call this a **pressure wave**.

Compare Figure 23-4 with Figure 23-3. In both pictures, disturbances are moving progressively. Both are waves, but the pressure wave moving in the spring is different from the shear wave moving in the rope (see Figure 23-5). In pressure waves the principal motion is forward-and-backward progressive motion.

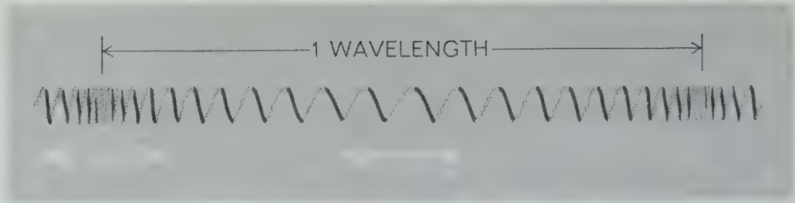


Figure 23-5 Diagram of a pressure wave

There are two quite different kinds of waves caused by pressure on water. One is like that described above in the experiment with a Slinky. There, the pressure you applied compressed part of the spring. When you released the pressure, a wave traveled through the coiled spring. Swimmers know that you can hear while underwater. Sound waves are pressure waves. These waves travel more rapidly through water than through air because water is less compressible than air.

The other kind of pressure wave in water you see at the surface of the water. Wind pressure raises the water into ripples, and then gravity pulls the raised water back down. You know from observation that the pressure-gravity waves travel in water. Their speed is related to, but slower than, the wind that causes them.

Can all kinds of waves progress through any medium? Experiments performed by physicists have provided the answer to this question. Pressure waves travel through all three states of matter. Shear waves travel only through solids. In Section 29-8 there is a discussion of the reasons for this difference.

Study Guide

1. Give the scientific definition of a wave.
2. Make a diagram of a wave and label all its measurements.
3. Define a shear wave and give an example of one.
4. Define a pressure wave and give an example of one.
5. Which kind of waves travel in water? Why?

23-4 CAUSES OF WAVES IN WATER

In the Slinky experiment you started a wave by pushing together some of the spirals of wire. The same thing will happen if you stretch a section of the Slinky. Try it. When you release the part of the spring that you pulled apart, a wave system moves through the Slinky. Thus, it appears that either pushing or pulling on a medium may cause a wave.

What could push or pull on water to start a disturbance moving? If a boat moves through the water, it pushes water out of the way. Do waves form from this pushing? If you don't know the answer, push your hand through some water.

Try some experiments. Fill a pan with water and let it stand until the surface is quiet. With your mouth just above one edge of the pan, blow across the surface of the water. Do waves form? What natural action have you imitated? The most common water waves are caused by the wind. These are called **wind waves**.

After the water has become quiet again, strike the side of the pan with a pencil. Does this cause waves? Is there any difference between the waves caused by blowing and those caused by hitting the pan? Observe the waves and think carefully before you answer this question. The moving air disturbed a thin film of water at the surface. Would you expect wind to affect the water deep in a pond or the ocean? When you jarred the pan, all the water was affected.

There is a natural action that jolts the water in an ocean, much as you jolted all the water in the pan. Earthquakes can do this in two ways, as shown in Figure 23-6. An earthquake

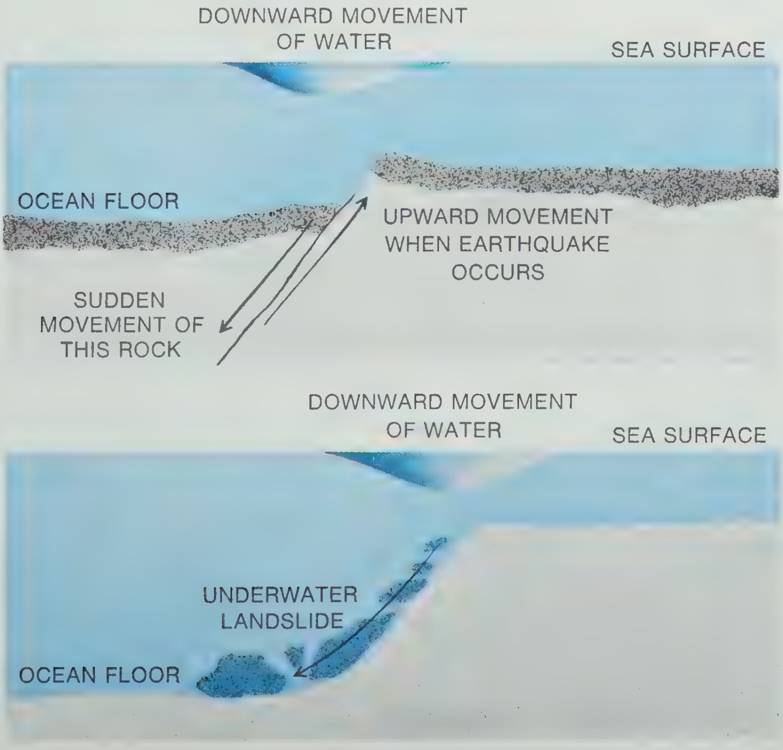


Figure 23-6 When the ocean bottom is violently disturbed, as by a landslide or an earthquake, the water above the disturbance may be forced into a wave called a tsunami.

Figure 23-7 In 1964 the great earthquake in Alaska produced a tsunami that damaged the waterfront of Seward, Alaska.

may cause a small section of the ocean bottom to drop or to rise. This violent action makes the water drop or rise, causing a wave.

An earthquake may also cause an underwater landslide, which in turn creates a water disturbance. Waves caused by earth movements are called **seismic sea waves**, or **tsunamis**. They are very long and low. Their wavelengths are about 200 kilometers (125 miles) and their periods approximate 1,000 seconds. Tsunamis may cause great damage when they reach a coast, as shown in Figure 23-7.(See Figure 23-8 for a comparison of the approximate periods of many kinds of water waves.)

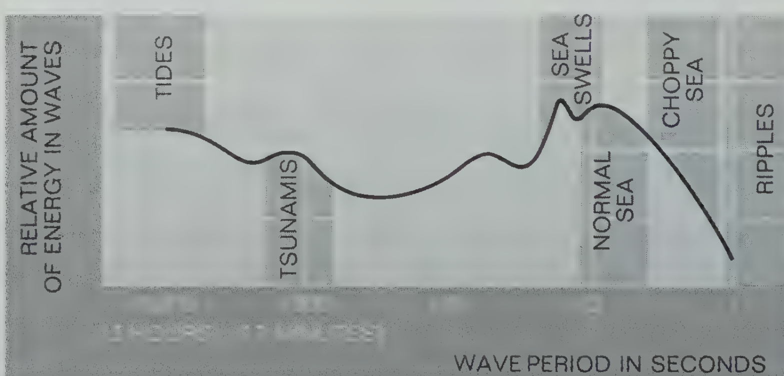


Figure 23-8 The periods of water waves

Figure 23-9 Along certain coasts the tides are very high and very low. The Bay of Fundy is an example of such an area. How must one tie up a boat under such conditions?

There is a third type of water wave. Those of you who live along the Atlantic and Pacific coasts know that twice a day there is a high tide and twice a day there is a low tide. Figure 23-9 shows an unusual example of this phenomenon. High and low tides are the crests and troughs of the **tide waves**. The tides are caused by the gravitational pull of the moon and sun on ocean water (see Section 33-3).

Figure 23-10 shows that high tides occur at the same time at opposite sides of the earth. Therefore, the wavelength and speed of a tide wave must be great. The speed of tide waves in the ocean is over 400 miles per hour. Their periods can be up to 12 hours and 25 minutes, with wavelengths of about 5,000 miles or even half the circumference of the earth.

The Gulf Coast has a different tidal pattern: one major high tide and one major low tide a day.

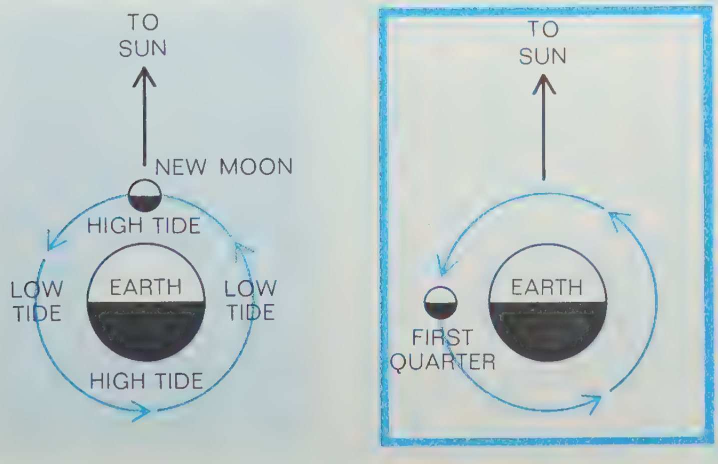


Figure 23-10 High tide is a slight bulging of the ocean.

23-5 WIND ON WATER

As you can see in Figure 23-7, waves can be destructive when they reach the shore. Even the ocean waves that break gently on a beach slowly change the shape of the coastline. The energy contained in a wind-caused wave has been transferred to the water from the wind. The wind has acquired energy as the result of uneven heating of the atmosphere. Thus, the energy in wind waves can ultimately be traced back to the sun.

When two fluids, air and water in this case, are moving at different rates and come in contact, there is turbulence. Air does not move smoothly along the surface of the ocean. Instead, some air twists into eddies (see Section 17-2). In an eddy, some of the air moves upward and some downward. This produces changing pressure on the surface of the water, as shown in Figure 23-11.

Fluids respond almost instantly to small changes in pressure. The downward-moving eddies of air depress parts of the water surface and cause other parts to rise. The depressions and bulges in the water surface are the beginnings of wind waves.

The raised areas of the water surface offer resistance to the flowing air. The pressure of the air is generally uniform on the raised water surface. On the lee side of a wave—the side away from the wind—the air is more turbulent than on the windward side. The pressure exerted on the lee side is less than that on the windward side. Therefore, the wave moves in the direction the wind is blowing.

As long as the wind continues to blow, waves will grow and move before the wind. They will grow until the wind pressure can build them no larger. What happens when the wind stops? The waves do not stop immediately. The movement of the water continues, but diminishes with time until

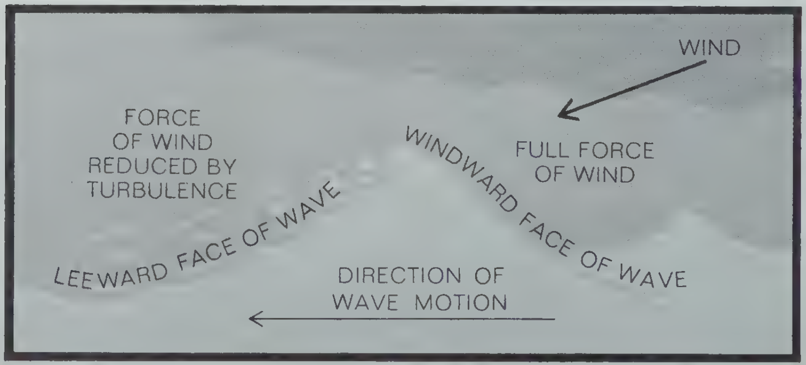


Figure 23-11 Unequal pressure of wind on water causes the surface of the water to ripple. Where is the reduced pressure shown in this diagram?

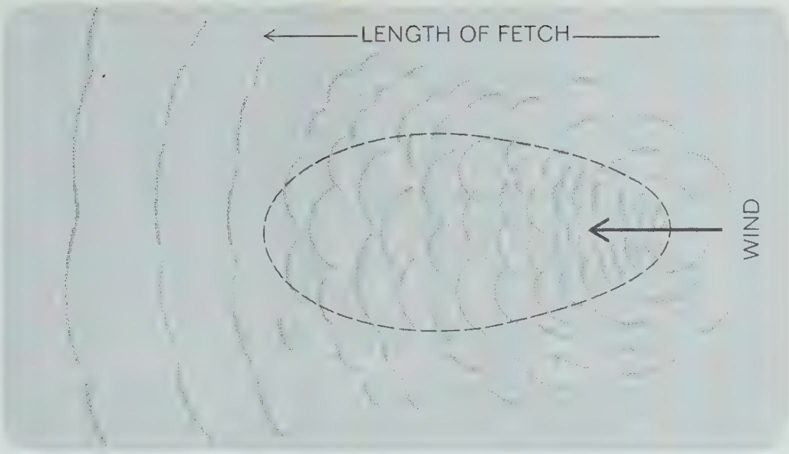


Figure 23-12 The development of ripples, waves, and swell

the water is quiet. These diminishing waves continue to move forward because of momentum. They will do so until friction converts all the kinetic energy of the moving water to heat.

23-6 WIND, FORCE, AND TIME

Strong winds build high waves. The longer the wind can act upon a wave, the more energy can be transferred to the water. Waves will stop growing when they have reached the maximum height for a certain wind velocity. You have learned in Section 22-5 that three factors determine the size of a wave: the wind velocity; the length of time the wind has been blowing; and the distance over which the wind has affected the water, or the fetch. Figure 23-12 shows the development of waves for a certain time and distance.

As soon as the wind that is building a wave dies down or the wave moves out of the range of the wind, the wave's height decreases and its wavelength increases. The wave continues to move across the surface of the ocean. But it now has a very low wave height and a very long wavelength. Waves that are no longer being built up by the wind are called **swells**.

In young waves that are still growing, there is a relationship between wavelength and wave height. The greatest height that a wave can have is about one seventh of its wavelength. Otherwise, the wave becomes too steep and will break, causing a whitecap. This relationship is shown in Figure 23-13. The angle at a wave crest cannot be smaller than 120 degrees.

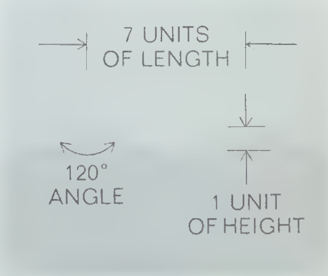


Figure 23-13 Theory of greatest possible wave height

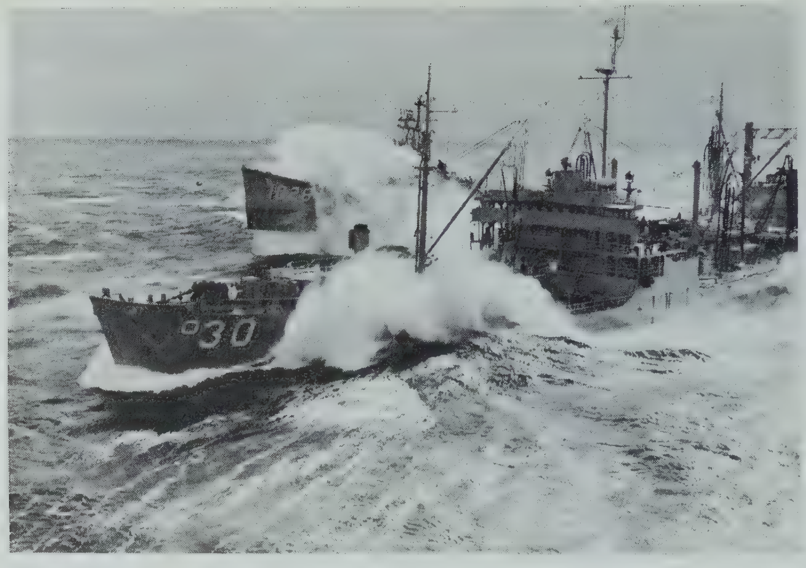


Figure 23-14 A high wave breaks on a vessel.

Swell and very high waves are seldom formed in enclosed bodies of water, even in lakes as large as the Great Lakes. The winds are strong enough, but they rarely blow for a long enough time, nor is the fetch long enough.

How high can a wave get? Gale-force winds (27 to 55 knots) that blow across a long fetch may build waves with wavelengths as great as 300 meters (1,000 feet). Such waves theoretically could have wave heights of one seventh of that, or about 43 meters (143 feet). Such large waves have been observed at sea, but they are rare. A hurricane wind (above 65 knots) blowing across a long fetch might create even higher and longer waves. Figure 23-15 is a graph that shows the relationship between wind velocity and wave height.

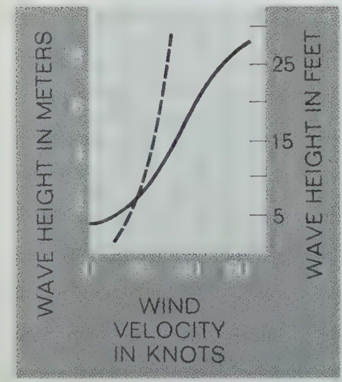


Figure 23-15 Wave heights depend upon the wind's velocity and its duration. A *knot* is 1 nautical mile per hour (1.15 statute miles per hour).

Study Guide

1. What is a tsunami? What causes it?
2. From Figure 23-8, determine what kind of waves have a period of about 10 seconds.
3. What type of ocean wave has the longest wavelength?
4. How does air move the surface of a body of water?
5. What factors determine the size of waves?
6. According to Figure 23-15, what would be the observed wave height produced by winds having a velocity of 50 knots? Give your answer in meters and in feet.

23-7 WATER MOVEMENTS IN A WAVE

The movement of a wave makes it seem that the water at the surface is moving in the direction the wave is traveling. This is not what is really happening. An object floating on the surface of the water does not travel along with a wave. Instead,

Figure 23-16 The wave moves forward, but the cork and the water stay in the same position unless blown by the wind. Why would the wind have less effect on this cork than on the vessel in Figure 23-14?

the object just bobs up and down in the water as the wave passes. It also appears to move a little forward as the crest of the wave passes under it. Then it moves a little backward as the trough passes. The motion is diagramed in Figure 23-16.

If you observe the movement of an object as a wave passes, you will see that the object moves with a circular motion. This means that the particles of water making up the wave must also be moving in a circle. The particles of water at the top of the circle form the crest of the wave. When the same particles are at the bottom of the circle, they form the trough of the wave.

The more wind energy transferred to the water, the larger the wave grows. The larger the wave, the larger must be the **circles of motion**. This has been demonstrated in the laboratory by measuring the radii of the circles of motion of objects being moved by waves. This evidence suggests that the size of the circles of motion is closely related to the amount of energy transferred to the water by the wind. The more energy transferred, the larger the circles of motion at the surface and the deeper they go beneath the surface.

23-8 HOW FAR DOWN DO WAVES AFFECT THE SEA?

When submarines are caught at sea during a storm, they submerge to avoid being tossed about by the high waves. When waves are 3 to 5 meters (10 to 15 feet) high, submarine crews usually find quiet water at depths of between 50 and 100 meters.

Earth scientists are interested in knowing how to calculate the depth to which water is disturbed by waves. Such knowledge helps to explain observations of the sea bottom made in offshore waters. You know that water molecules cannot be

observed directly. What scientists must do is observe the effect of the motion of water upon visible particles such as mud, sand, and silt. Scientists using *scuba* equipment have watched and photographed the movement that takes place in a circle of motion.

Earth scientists are also able to generate small waves in experimental, glass-sided wave channels. By adding visible material to the water, they can study the motion of the water at several depths. Figure 23-17 illustrates the motion of water in a wave channel.

In Table 23-1 you will find information about the size of the circles of motion we believe exist under waves of various sizes. The values have been gathered from direct observation and by calculation. The table shows that the longer the wave period and wavelength, the deeper the disturbance.

A second relationship shown in the table involves a comparison between young wind waves and swell. In waves, the radii of the circles of motion increase with increasing wavelength. In swell, the radii decrease with increasing wavelength. How would you explain this change in behavior?

Young waves receive energy from the wind faster than they expend it. That is why they grow. In swell, energy is being used up, and no new energy is being gained from the wind. Swells are considered old waves.

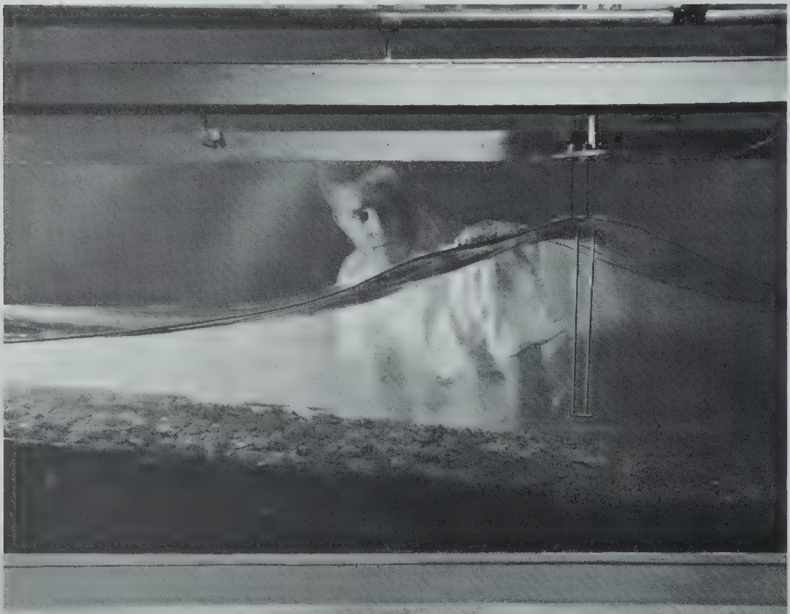


Figure 23-17 Long, glass-sided troughs containing water and a mechanical wave maker are used to study the motion of water in waves.

Table 23-1 Radii of circles of motion

Wavelength	*Period*	*Depth*			
(meters)	*(seconds)*	*0m*	*2m*	*20m*	*100m*
For waves		Radii of circles (centimeters)			
6	2	12	1.7	0	0
25	4	50	31	0	0
56	6	100	81	11	0
100	8	250	220	71	0.5
156	10	350	324	158	7
225	12	403	380	218	25
For swell					
396	16	502	483	364	104
506	18	401	390	312	116
624	20	248	242	201	90

23-9 WAVES FEEL THE BOTTOM

What happens when waves reach the shore? They obviously cannot move across the land. In the next chapter you will learn what happens to the land where it meets the ocean. Here you will learn what happens to waves as they meet the shore. As waves approach the shore, the water becomes more and more shallow. What does this do to the structure of a wave?

Somewhere offshore, the deepest circles of motion and the shoaling sea bottom will meet. Where the depth equals one half the wavelength, the wave touches bottom. The wave is then said to **feel bottom**. For example, swells with crests 100 meters (330 feet) apart will feel bottom in 50 meters (165 feet) of water.

As the water in the circle of motion brushes against the bottom, the water rapidly transfers energy to the sediments. This causes the sediments to move. The loss of energy changes the circle of motion to an ellipse, as shown in Figure 23-18. Since the wave loses energy to the bottom, its forward motion slows down. Therefore, the shallower the water, the slower the wave. When a wave feels bottom, its wavelength decreases, and its wave height increases. In the next chapter we shall see how this slowing down may turn the wave toward shore.

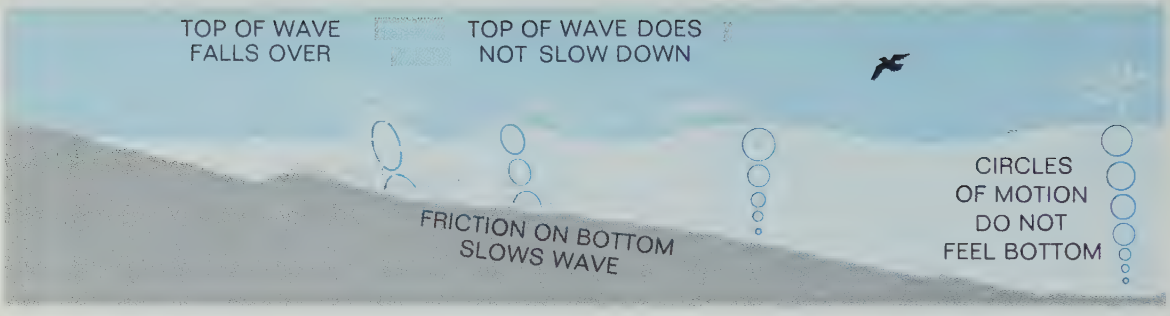


Figure 23-18 As a wave comes ashore, it feels bottom, stirs up the sand, moves the sand shoreward, and thus builds a sandbar.

The lower part of the ellipse of motion drags on the bottom. This means that the upper part of the ellipse is moving faster than the lower part. What would happen to you if your feet moved forward slower than the upper part of your body? You would lose your balance and fall forward. The same thing happens to a wave. The bottom of the wave moves slower than the crest. The top of the wave curls forward and crashes downward. When a wave does this, we call it a **breaker**. The wave actually breaks apart. When the wave breaks, it loses its energy rapidly to the material on the sea bottom. This stirs up the sea bottom and moves the sediments. Such energy has been felt by anyone who has been hit by a breaker at the seashore.

Study Guide

1. Why is water that is deep under a wave not disturbed by the wave?
2. By what two methods can earth scientists study the movement of water under a wave?
3. Explain what is meant by *feeling bottom*.
4. Why does a wave form a breaker at the shore?
5. What happens to the energy in a wave after it breaks?

SUMMARY

All waves are disturbances that move progressively across or through a medium. Ocean waves are most frequently caused by pressure and turbulence between the water and the atmosphere. In addition to wind waves and swell, there are tsunamis and tide waves.

In a wind wave, the particles of water under the surface travel in a circle of motion. The size of the circle of motion of the water is related to the wavelength and the wave height. The radius of the circle diminishes with depth.

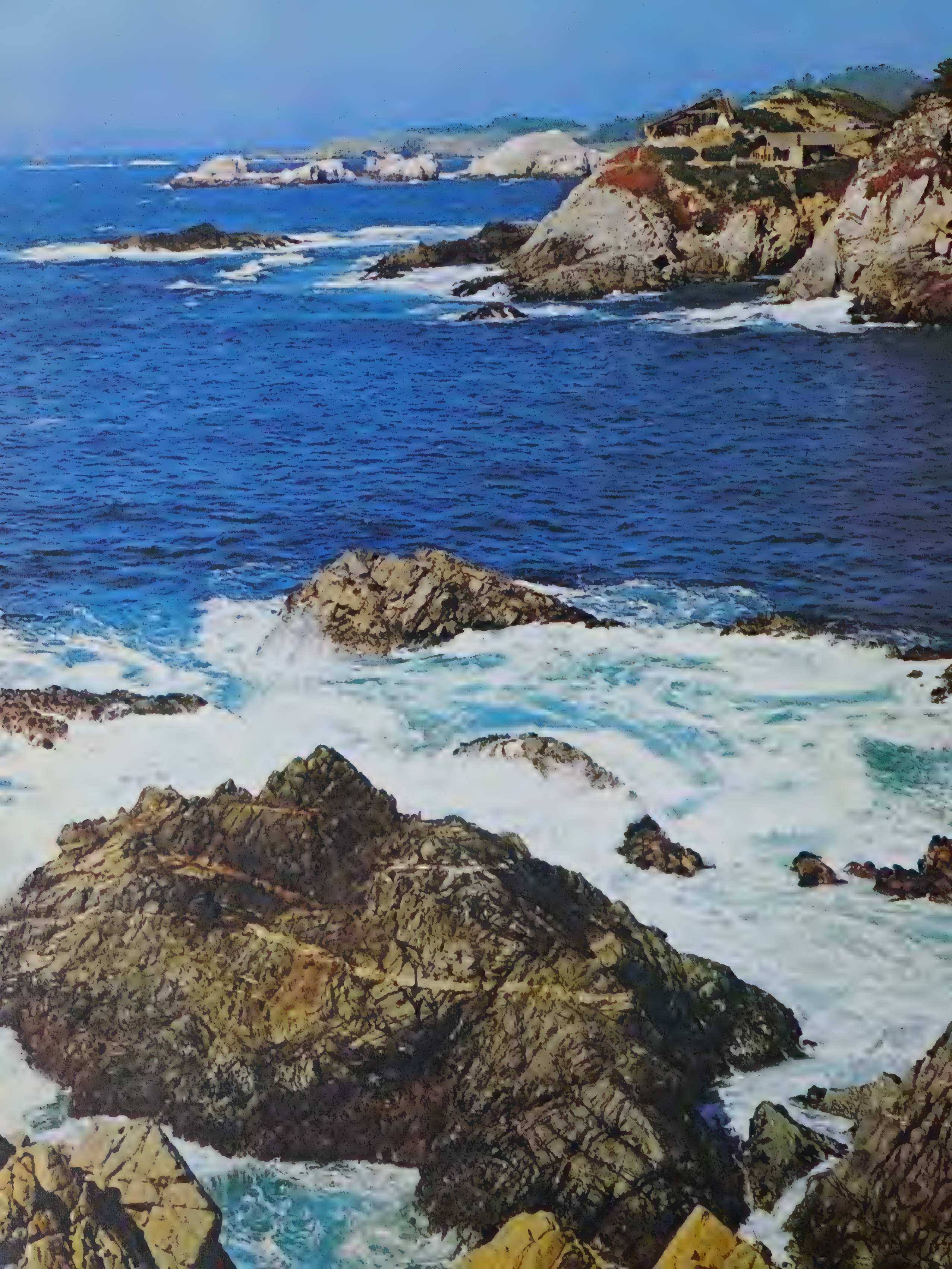
When the lowermost circles of motion come in contact with the sea bottom, the bottom sediments are stirred up and the water slows down. The wavelength decreases, and the crest of the wave continues at the same speed, becomes higher, and soon curls over and breaks up.

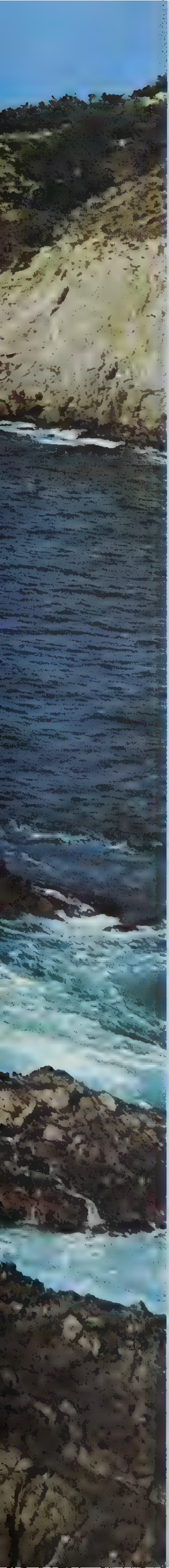
REVIEW AND DISCUSSION QUESTIONS

1. How does the wavelength of a wave affect its ability to move sediments on the ocean floor?
2. What is the greatest wave height possible of a wave that has a length of 21 meters?
3. Often, just before a tsunami hits a coastal area, sea level drops greatly in that area. Occasionally, before a tsunami occurs, the sea bottom may be exposed in a harbor. Explain this large drop in sea level that precedes a tsunami.
4. Explain why sound waves and water waves must be pressure waves, not shear waves.
5. The wavelength of a tide wave averages about 8,900 kilometers. Why are these waves so long compared with other kinds of water waves?
6. In Figure 23-8, what is the average wave period for swell?
7. The water particles in a wave move in a circle of motion, but not forward or backward to any extent. Why will an object floating in the open ocean eventually reach land?
8. Scientists have discovered that on the average the wavelength of waves is between 20 and 30 times their wave height. How high could a wave with a wavelength of 50 meters be?
9. From Figure 23-12, describe how waves change with time and distance.
10. Explain why the following formula for calculating the velocity of a sea wave is correct.

$$\text{Wave velocity} = \frac{\textit{Wave length}}{\text{Wave period}}$$

11. What is the speed of a wave that has a period of 1.6 seconds and a wavelength of 4 meters?
12. Describe the ways that energy gets into and leaves the water in the oceans.
13. In Figure 23-15, what is the observed wave height for a wind velocity of 50 knots?





CHAPTER 24

THE SEA MEETS THE LAND

Wherever the sea meets the land, there is action. In one place a rocky headland juts into the sea and is battered by the surging storm waves. In another place the smooth sweep of a curving beach of sand is forever shifting as waves wash across it. What is now an island may someday be tied to the land by a broad stretch of sand. What is now a peninsula may be partly flooded by the sea and an island may be formed. The sea so changes the outline of a continent that maps are always slightly out of date.

Over the millions of years of the earth's history, there have been times when the sea has risen far up on the land. As we have seen, in Cretaceous time, a hundred million years ago, much of what is now the central part of the United States was ocean bottom. What is now shoreline has not always been so, nor will it remain so.

24-1 TWO TYPES OF COASTS

The relationship between the level of the land and the level of the sea is subject to change. Sometimes this is caused by upward or downward movement of the land. At other times, sea level may change when water is added to or removed from the ocean. How may this occur? Both these actions affect the coastlines of the continents.

The area where the sea ends and the land begins is not a fixed one. Where a rocky headland juts into the ocean, waves batter the rock. Very slowly the rock yields to the force of the water and is eroded. In a single day, storm waves can change the whole appearance of a sandy beach. Twice a day, the rising and falling tides shape the coastline.

When the sea rises with respect to the land over a long period of time, the coast is drowned, or submerged. It is then called a **submergent coast**. If the opposite occurs, the exposed sea bottom becomes part of an **emergent coast**. The

A headland on the California coast

land that was once sea bottom becomes part of a new **coastal plain**.

The Atlantic Coast contains excellent examples of different forms of coastlines. The coast of Maine is a beautiful, rugged, and rocky submergent coast. The sandy beaches from Georgia to Texas are the seaward edge of an emergent coastal plain. From southern New Jersey to South Carolina, the coast is an ancient emergent coast that has recently been flooded by the sea and become submergent again.

The Pacific Coast has been changing more rapidly than the Atlantic. Many miles of the shoreline in California are rocky emergent coast. Coastal mountains that rose out of the sea are still growing. Clinging to the sides of the mountains are small, narrow patches of uplifted coastal plain. Parts of the coast south of Los Angeles are emergent, with a broad coastal plain. North of Puget Sound, Washington, the coast is generally submergent.

24-2 EMERGENT COASTS

Figure 24-1 is a map showing the outline of the United States during the Cretaceous Period. Most of the central portion of the country was sea bottom at that time. It appears that we are now living in a period of raised continents. Whether this is due to a rising of the land or a dropping of the sea level is not completely known. Probably it is the result of both, but the uplift of continents may be the more important. The

Figure 24-1 The landmass of the United States during the Cretaceous Period (about 135 million years ago)

Figure 24-2 A geologist inspects a section of a core of the earth's crust. Numerous cores have been obtained in the search for oil.

emergent coasts have revealed ancient sea bottoms. Let us see what these coastal plains can tell us about the past.

The modern coastal plain of Georgia was underwater in Cretaceous time. We know this from the fossils contained in the rocks. In the southwestern corner of the state, about 3,000 meters (10,000 feet) of marine sediments have been deposited on the basement crystalline rocks. On the map, you see a line labeled *fall line*. That is about where the coastline was during the Cretaceous Period. North of the fall line, the surface is composed of the metamorphosed rocks of the Appalachian Mountains.

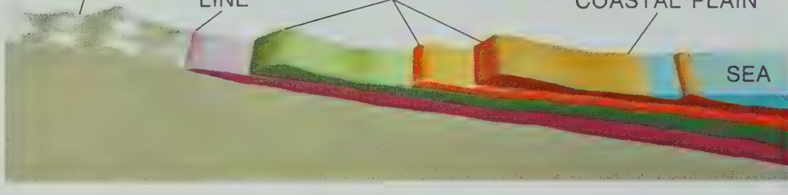
It is called the fall line because waterfalls often occur where the coastal plain meets the higher oldland.

Geologists have developed a way of studying the rocks below the surface. Using a hollow drill called a **corer**, they cut and remove from the earth a cylinder of rock called a **core**. The pieces of the core are laid out in the order in which they are brought up. The core forms a geologic column of the area.

The sedimentary rocks at the bottom of a core taken from the coast of Georgia are of Cretaceous age—about 135 million years old. This is the same age as that of the rocks at the surface near the fall line, about 280 kilometers (175 miles) away. The uppermost rocks in the core are about 18 million years old. Above them are unconsolidated sediments, mostly sands and clays.

When the rocks in the core are compared with those on the surface of the coastal plain, we find they are related. Let us take an imaginary trip inland from the coast. The uppermost

Figure 24-3 As the land was lifted from the ocean, forming a coastal plain, there was a certain amount of warping of the crust. Cuestas are the result of such lifting and warping.



rock in the core is a sandstone. Slightly inland from the coast this same rock appears at the surface, eroded into gentle hills. Soon the surface rock changes to the same kind found in the second layer in the core. At this distance from the coast, the scenery changes. Here we find a **cuesta**. This is a ridge having a gentle slope facing toward the coastline and a steep slope facing inland (see Figure 24-3).

cuesta (KWES tuh); Latin: *costa*, side.

As we proceed farther inland on our imaginary trip, we find that the surface rocks are the same as those that appear deeper and deeper in the core taken from the coast. Each time we come to an exposure of a hard sedimentary rock, we find a cuesta. Each time we travel over softer sediments, the surface is shaped into gentle hills. Finally we reach the steep fall line. Here, toward the sea, the surface rocks are the same as those found at the bottom of the core—Cretaceous sediments. Inland appears the *oldland*, composed of crystalline rock.

24-3 HOW DID THE COASTAL PLAIN FORM?

Suppose the shore in Cretaceous time was at the edge of the modern Appalachians in Georgia, where the fall line is now. This would explain the presence of the Cretaceous sediments at the fall line and at the bottom of the core taken at the present coastline. As you go inland from the coast to the fall line, each successive surface rock is older. The youngest sediments are those at the surface at the coastline. Such a condition could have occurred if the shoreline slowly retreated from the fall line in Cretaceous time to where it is now (see Figure 24-4).

The fall line is about 300 meters above present sea level. It is doubtful that the oceans have lost that much water since Cretaceous time. There is some evidence, as you will learn in the next chapter, that the ocean bottom has sunk.

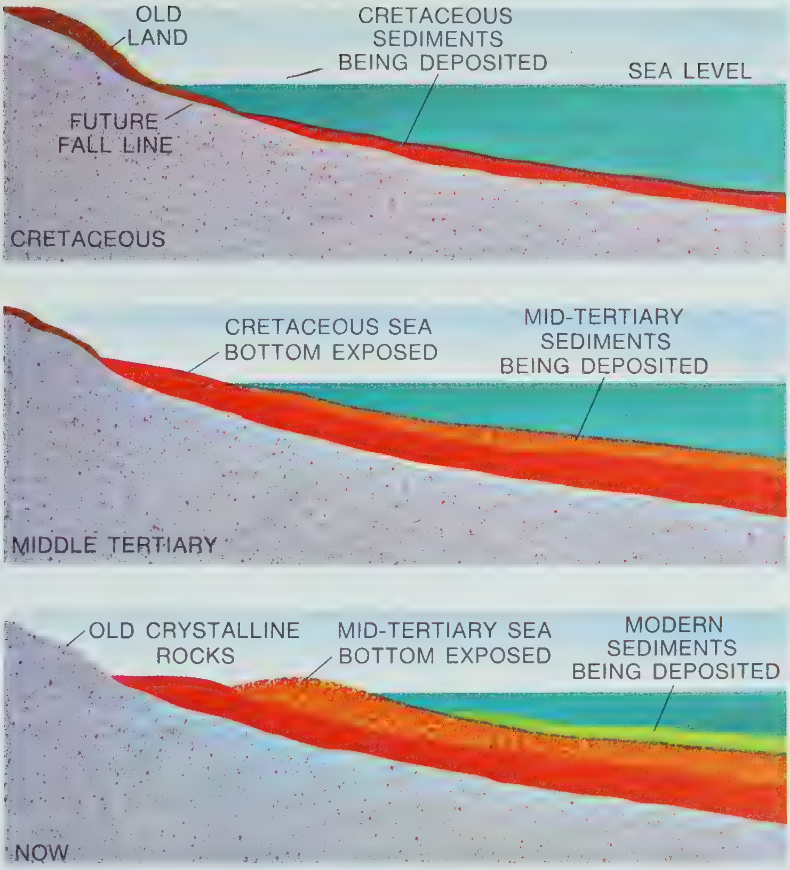


Figure 24-4 As the continent has lifted since the Cretaceous Period, thick layers of ocean-bottom sediment have become dry land. The oldest surface sedimentary rock is now found about 175 miles inland from the present shoreline, or about 1,000 feet above the present sea level.

It seems quite probable from geologic evidence that the Appalachian Mountains have risen about 300 meters in the last 100 million years. This uplift also raised the sea bottom at the coast above sea level. Therefore, the Georgia coastal plain and other emergent shorelines are exposed sea bottom.

Exposed sea bottom is relatively smooth and composed mostly of unconsolidated sediments. Beneath these deposits are the sediments that have been compressed into rocks. Streams that reached the sea at the ancient shoreline usually continue across the uplifted plain to the new shoreline. New streams may also form.

24-4 SUBMERGENT COASTS

When sea level rises with respect to the land, one of the first results is the drowning of the river valleys that lead to the ocean. The high ridges that flank the valleys remain above

sea level and jut out along the new shoreline. These are called **headlands** (see the photograph at the beginning of this chapter). The water-filled river valleys are called **bays**. Chesapeake Bay in Maryland is an example, as are the bays along the coast of Maine.

After the land has been submerged, the irregular headlands are attacked and eroded by the waves and currents of the sea, as you will learn in Section 24-11. Debris eroded from the headlands begins to fill the shallow bays. Given sufficient time, the irregular submerged coastline will be straightened by waves and currents. If the right conditions exist, sandy beaches may form, and the character of the entire coastline may be changed.

24-5 MARINE TERRACES

The geologic movements of the land interrupt the orderly wearing away of the shores by the sea. We can see this best along the shores of the Pacific Ocean in California. If the sea bottom of a coast has been underwater for a long time, the waves and tidal currents may have eroded it to a flat structure called a wave-cut bench or marine terrace.

Some of the most carefully studied marine terraces in the world are those along the coast of Palos Verdes, California. You can see several flat-topped rises, one above the other, from the shoreline to the horizon. Each of these flat structures is a marine terrace. The highest one is about 300 meters above sea level.

Figure 24-5 An emerged wave-cut bench, or terrace, at Cape Perpetua, Oregon

Geologists have discovered some terraces that are 150 meters below sea level in this same area. In each case, the terrace must represent a time when waves eroded rock very close to sea level.

Observation of the marine terraces at Palos Verdes led geologists to pose the question, How can we account for the terraces both above sea level and below sea level in deep water? We know that terraces are cut just offshore in shallow water. Could some of the terraces in California have been cut in deep water?

There are two forms of evidence that answer the question with a *no*. We know of no action of the sea that could erode solid rock at great depth. You have already learned that even the largest waves do not disturb water very deep in the ocean. The second form of evidence is the shells on the surface of marine terraces. Most of them are shells of shallow-water animals.

How then can we explain marine terraces found both above sea level and below sea level in deep water? Geologists believe the marine terraces are evidence of changing sea level in the past. All the terraces were originally formed in shallow water. Those now above sea level must have been formed when the land was lower than it is now. Those now in deep water must have been formed when the land was higher than it is now.

Study Guide

1. Where are the emergent and submergent coasts around the United States?
2. During the Cretaceous Period, was the sea level lower, or higher, than it is now?
3. Where in Georgia are Cretaceous sediments usually found at the surface?
4. Give an example of a drowned river valley.
5. Where do you find cuestas?
6. What is a marine terrace?

24-6 WAVES COME ASHORE

Did you ever wonder why waves approach a beach almost parallel to it? Even though the wind is at right angles to the beach, the waves roll in almost head on. How does this come about?

When waves move toward a beach at an angle, the end of the wave front nearest the shore enters shallow water before

Figure 24-6 Wave fronts bend as they approach the shore, and they strike the beach almost parallel to it.

the rest of the wave. What does this do to the wave front? Because the shore end of the wave feels bottom, it slows down. When that part slows down, it turns toward the shore, as you can see in Figure 24-6. Notice where the wave fronts are bent. As more of the wave front feels bottom, it also turns toward the shore. Such bending of a wave front is called **refraction**.

24-7 FOCUSING WAVES

If you live along the West Coast, you have seen long, rolling swells. The prevailing westerlies over the North Pacific have thousands of miles to produce this swell. That is why surfing is so good on the West Coast. The surf from the breaking swell varies from beach to beach, depending on the slope of the bottom. What do you need besides swell to have large breakers? You need a shallowing beach. Breakers do not form where beaches drop off quickly.

Figure 24-7 shows a beach with offshore ridges and a valley perpendicular to the shore. The wave front of the swell does not feel bottom along the valley. Therefore it hits the beach without forming a large breaker.

But look what happens to the part of the swell that passes over the ridge. Because the ridge is shallow, the swell feels bottom far from shore. What happens when the wave feels bottom? It slows down, and it refracts, or changes direction. Notice that this happens on both sides of the ridge.

At this point you must recall something from the last chapter. Waves have a certain amount of energy. What happens to this energy as a wave moves from deep to shallow water?

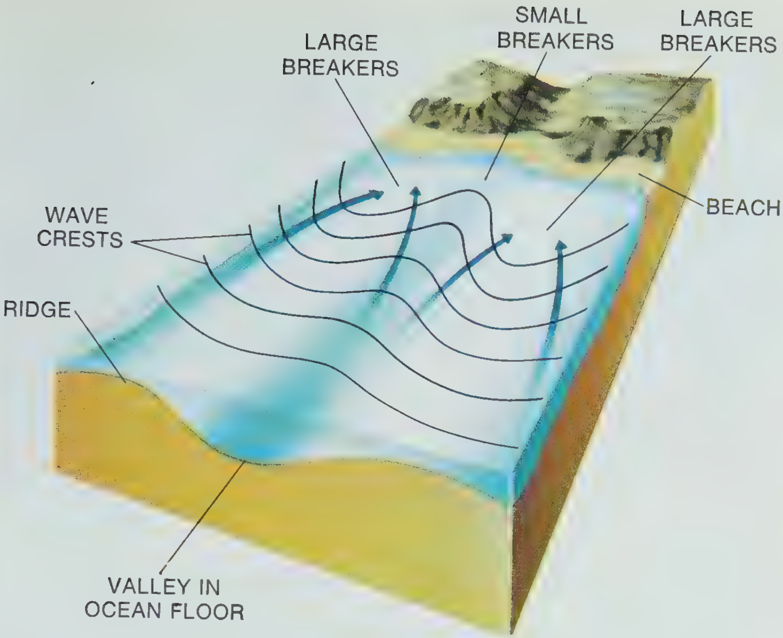


Figure 24-7 The shape of the submarine topography determines the size of the breaker that a wave will form.

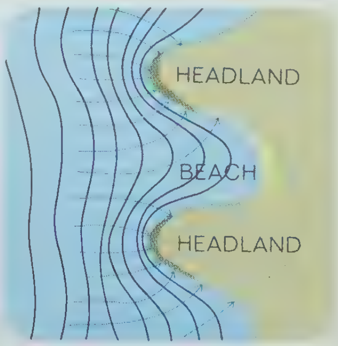
The wave slows down, and its wavelength decreases. Its excess energy increases its wave height.

When the swell moves over the ridge, it not only bends, but increases in height. The ridge acts as a magnifying lens. It focuses the growing waves on a section of the beach where the ridge meets the land. At that point the breakers are enormous. Farther along the beach, where the underwater valley meets the land, the breakers are small.

Where are underwater ridges usually found? The high points, or headlands, along a coast when followed out to sea become underwater ridges. The ridges focus the waves on the headlands, as shown in Figure 24-8. The focused waves batter the headlands and gradually erode them.

The eroded material of the headlands is carried into quiet bays. Such sediments are deposited, forming a sandy beach. Why are the waves not focused on the bay?

Figure 24-8 Underwater ridges that lead to headlands focus the energy of waves onto the headlands.



24-8 CURRENTS ALONG THE SHORE

Watch the waves move toward you at the shore. How does the water return to the sea? This depends on the angle at which the waves approach the shore. Water returns to the sea by moving under the incoming wave. This is the **undertow**, and it can be strong enough in heavy surf to pull you off your

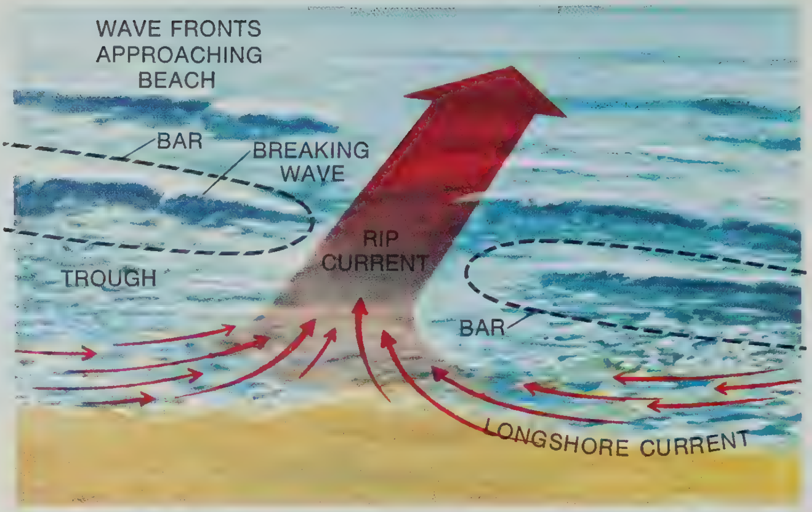


Figure 24-9 Longshore currents are usually caused by the wind. The accumulation of water close to the beach causes swift and narrow rip currents, which flow seaward.

feet. However, it ceases to pull a few seconds before the next wave breaks.

Waves often approach the shore at a small angle, as in Figure 24-9. They also roll off the beach at a small angle and start a current flowing along the shore—the **longshore current**. That is why you often drift along the shore when you are swimming.

Longshore currents usually feed into a stronger current flowing out to sea. This is the **rip current**, and it can be dangerous. The rip current usually exists when there is a channel between offshore sandbars. Why are there breakers in between the rip currents? If you are caught in a rip current, swim out of the current by going along the shore, not toward it.

Study Guide

1. What makes a wave slow down as it approaches shore?
2. Explain what may happen to the direction of a wave front as it approaches shore.
3. Why is there so much swell on the West Coast of the United States?
4. Give an example of refraction.
5. In which direction would you swim to get out of a rip current?

24-9 BEACHES

To the earth scientist a **beach** is a moving deposit of material between land and water. The material is being moved along the shore and along the offshore bottom.

We usually think of a beach as a broad expanse of fine, white sand bordering the ocean. But this is only one kind of beach. Beaches form an almost continuous fringe along the continents and islands. They may be less than a meter or more than a hundred meters wide. This depends on the steepness of the land where it meets the sea.

Where have you seen wide beaches? Where have you seen narrow beaches?

The materials of which beaches are made range from fine clay to large boulders. There are **sand beaches, pebble beaches, cobble beaches,** and mixtures of all three. A **shingle beach** is built of small, flat stones arranged by waves into a pattern like the shingles on a house. When a beach is built of silt or mud, it is called a **mud flat**.

Good recreational beaches do not line the ocean everywhere. However, there is usually some kind of beach wherever the sea meets the land. The only exception to this is where steep cliffs continue below sea level.

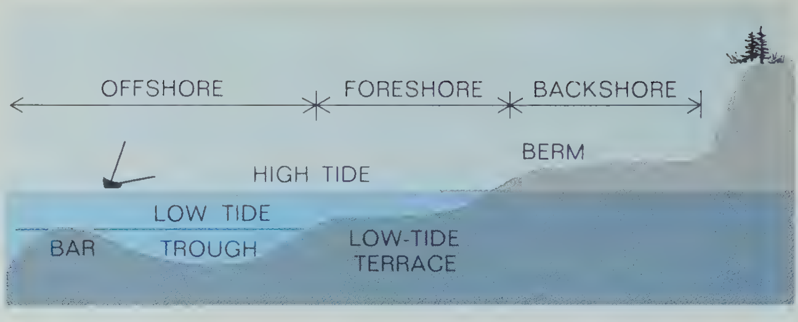
24-10 CHANGING BEACHES

Beaches are formed and changed by combinations of waves, currents, and winds. From tide to tide or day to day the changes are small. From season to season and year to year, however, there can be obvious changes. Perhaps the greatest changes are noticed after a bad storm.

As you are beginning to realize, beaches vary. Even all sand beaches are not the same. The sand beaches on the West Coast, facing the Pacific swell, differ from the sand

Figure 24-10 (*Left*) Pebble beach (*Right*) Sand beach

Figure 24-11 The structure of a typical beach



beaches on the East Coast, facing the choppy water of the Atlantic Ocean. Any place where waves transport and drop silt, sand, or stones is considered beach. The sandy terrace shoreward of the area that is covered at high tide is called a **berm**. See Figure 24-11 for a diagram of a typical beach. The beach is considered to extend offshore to a depth of about 10 meters (30 feet). At this depth, waves tend to deposit sand, which forms a ridge, or **bar**.

Waves, currents, and tides move the sediments that form beaches. There is a delicate balance between the factors that build a berm and those that destroy it. A wave must be just powerful enough to erode sand from the ocean bottom and transport it to the berm. This is what usually happens in the summer. At that time the berm usually grows seaward.

In winter the waves are more powerful. They bring sand ashore, but their backwash is so powerful that they remove more sand than they deposit. Winter waves produce offshore bars with this sand at the expense of the berm. Figure 24-12

Figure 24-12 The changing beach of Carmel, California. Small summer waves build the berm 200 feet seaward. The large waves of winter remove most of the berm.

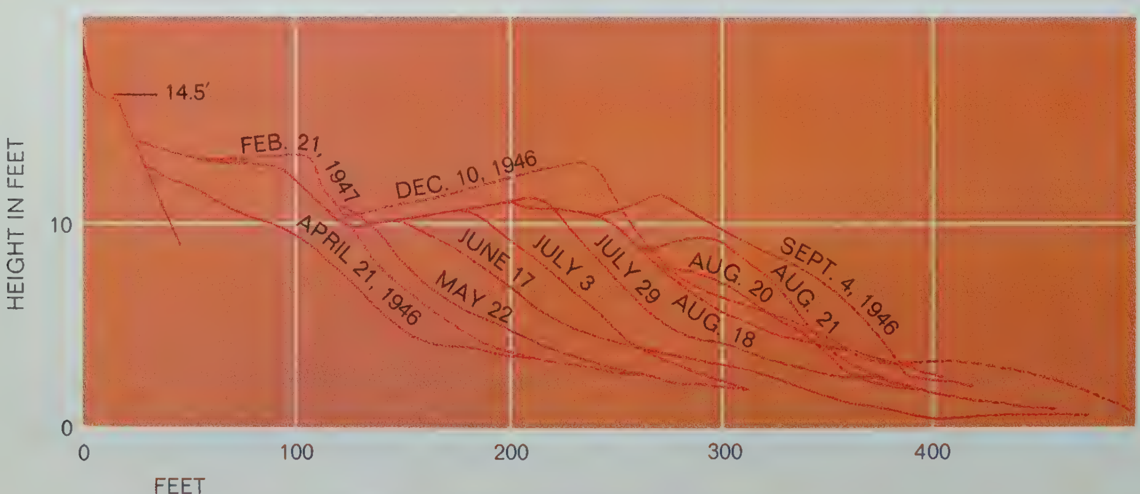


Figure 24-13 Sea stacks and caves are carved from the headlands of submergent coasts.

shows the seasonal cycle of the berm of the beach at Carmel, California. Where does the sand come from? Why don't beaches on the East Coast and Gulf Coast change as much as the Carmel Beach?

Beach sediments usually come from a distant place. Rivers carry sediments from the land, and these are sorted and distributed by currents, tides, and waves. In glaciated areas, such as the coast of New England, waves work over the glacial till. In lower latitudes many beaches consist of fragments of shells and broken coral.

Cliffs, like those shown in Figure 24-13, can be the source of sediments. A crashing wave may exert tons of pressure on each square inch of the cliff. As waves pound against the rock, air trapped within the cracks is compressed. Such pressure loosens rock, and the fragments fall into the ocean. In this way **sea caves** and **sea stacks** are formed. The eroded material from a cliff may form a beach at the foot of the cliff, or it may be deposited somewhere else by longshore currents.

24-11 BARRIER BEACHES

There are two movements of water involved in beach formation and erosion—onshore currents and longshore currents. The onshore currents are very important in building barrier beaches, the type of beach that forms much of the United States coastline. This includes the coast from the Rio Grande in Texas, around the Gulf Coast, and all the way up the Atlantic Coast to Long Island. There are only small bits of this kind of coastline on the Pacific Coast. The only requirement for a barrier beach is plenty of loose sediment offshore and medium-sized waves.

As waves break offshore, the bottom sediments are tossed forward. The material is deposited closer to shore when the

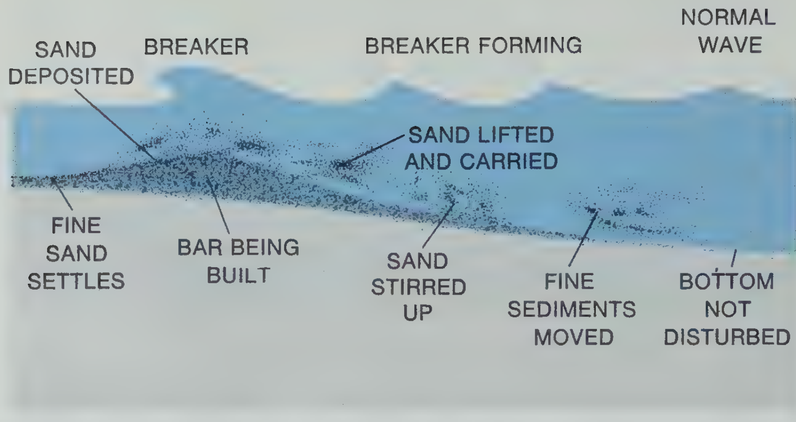


Figure 24-14 Sand bars are formed where waves deposit the sand they have removed from farther offshore. Sand bars are also formed when powerful waves wash sand from a beach.

waves slow down. Some is returned to deep water by undertow and rip currents, but some remains where it was deposited, forming a bar. As this deposit grows, it begins to interfere with the free flow of waves toward the shore. The sea becomes shallower where the bar is growing. Waves feel bottom in that area and tend to break there. Then the bar grows faster and faster.

Eventually, enough material is deposited to form a bar that is above water at low tide. Waves with a greater-than-average wave height will deposit even more sediment on the bar. In time, the bar will be built well above the average sea level. Large bars become known as **barrier bars**, or **barrier beaches**.

The water between the barrier bar and the mainland is protected from the waves of the open ocean. It is quiet water, which rarely develops large waves. This sheltered body becomes known as a **lagoon** or a **sound**. Turn back to Figure 19-15, showing Cape Hatteras, and locate the barrier beaches and sounds.

A sound is generally large, and a lagoon small. Pamlico Sound, between the mainland of North Carolina and the barrier beach that forms Cape Hatteras, is about 23 miles across. A lagoon may be only a few yards wide.

The sediments being carried to the sea by streams will usually be deposited in the lagoon. Eventually, they may fill the lagoon and turn it into a marshy mud flat. Plants that can grow in brackish water will trap more sediment and help build the level higher. If enough deposition takes place in the lagoon, a strip of dry land may develop and connect the barrier beach to the mainland.

Study Guide

1. What partly determines the width of a beach?
2. List the factors that change a beach.
3. What is the berm of a beach?
4. Study Figure 24-12 and state the chief difference between a beach in summer and a beach in winter.

5. Where do the sediments of a beach come from?
6. Where in the United States are barrier beaches found?

24-12 OTHER SAND FORMATIONS

The headlands of a submergent coast are battered and eroded by waves. The sandy sediments produced by the action of waves on a rocky coast are moved by local currents. These currents tend to be strong near the headlands, which jut into the sea. In the bays the currents are weaker. On the sheltered side of the headlands the current loses its force and drops its load. As a result, an underwater bar of sand is formed. If this bar grows to the surface and is attached to the land, it is called a **spit**. If longshore currents form a spit into a curve, it is called a **hook**, such as Sandy Hook, New Jersey.

Sometimes a spit reaches partly across the mouth of a bay. It is then called a **bay-mouth bar**. Figure 24-15 shows that with enough time and sand the bay-mouth bar will close the

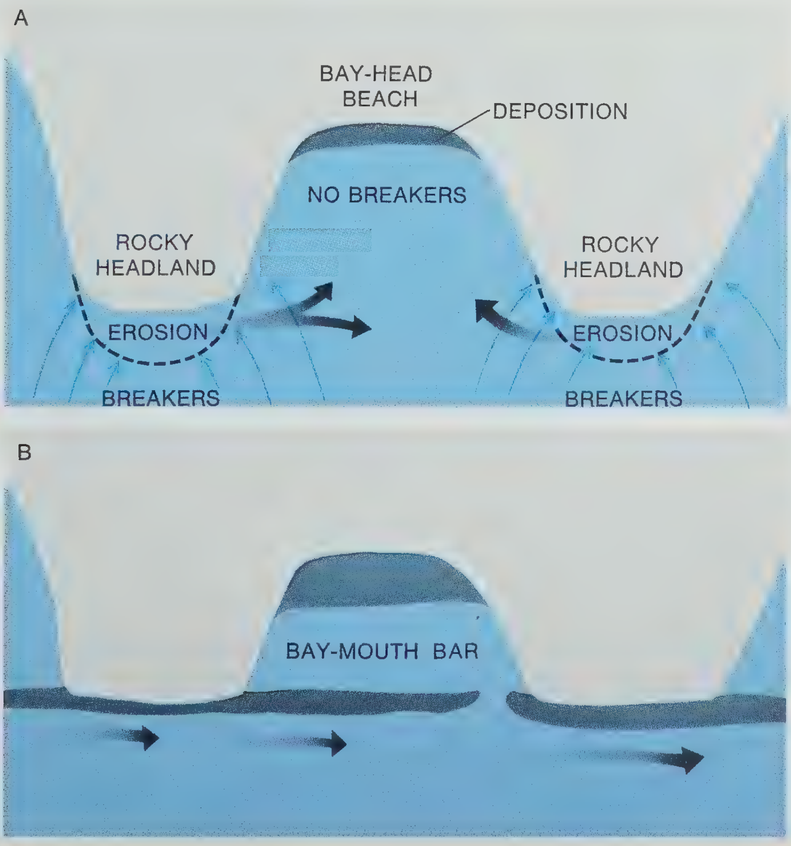


Figure 24-15 The formation of a bar across a bay helps to smooth out the shoreline of an irregular submergent coast.

bay. Many bays are kept open only by dredging across the bay-mouth bar. Do you see how barrier beaches and bay-mouth bars straighten a coastline?

One of the features of a submergent coast is offshore islands, often more or less in line with a headland. Such an island may be separated from the mainland by relatively shallow water. This will disturb currents between it and the mainland. Sediments carried by those currents will be dropped, and the bottom will build to the sea surface at low tide. Once this happens, storm waves will pile material at that place. Under ordinary conditions of the sea, the island will then be connected to the mainland by dry land. Such a structure is called a **tombolo**. This is part of the straightening and smoothing process accomplished by waves and currents.

24-13 TIDES ON THE SHORE

The tide is a wave raised by the gravitational effect of the moon and sun on the ocean. Theoretically, this wave could have a wavelength of about half the circumference of the

Figure 24-16 Spruce Head Island, Maine, is tied to the mainland by a sand formation called a tombolo.

Figure 24-17 The tidal bore of Tsientang Kiang estuary. The junk captains schedule their trips up and down stream to coincide with the rush of the tidal bore.

earth. Its wave height in the open ocean is probably less than 1 foot. We assume this because high tide on a small mid-ocean island is only about 1 foot. Why do other places have much higher tides?

Since the wavelength of the tide wave is great, the tide wave feels bottom in water possibly as deep as 200 meters (600 feet). As the tide wave approaches the coast, the shallow fringes of the continent act as a wedge under the wave. This raises the surface of the oncoming tide wave.

At least two things may happen to a tide wave when it touches bottom and enters a bay or estuary. Friction along the bottom and the sides slows it down, and the height of the wave increases. In long, funnel-like bays, such as the Bay of Fundy, New Brunswick, a layer of water 100 meters deep moves up the bay. The tide wave increases in height as it moves up the bay into shallower and shallower water. This growing tide wave is called a **tidal bore** (see Figure 24-17). In such an area the average difference between high and low tide is about 9 meters (27 feet). Think of the problems of tying a boat to a dock under such conditions. What would you have to do?

The movement of tidewater causes currents. As tides come in and out, so do the tidal currents. These currents distribute the sediments brought by rivers or loosened by wave action on a rocky coast.

An example of their work is illustrated by the presence or lack of presence of a delta at the end of a river. Where the tides are small, there are practically no tidal currents to sweep away the delta-forming sediments at the mouth of a river. For this reason the Nile has a delta in the Mediterranean, and the Mississippi has a delta in the Gulf of Mexico. Both of these bodies of water have relatively small tides, if any. On the other hand, the great Amazon River with all its sediments has no delta. Tidal currents flush out its mouth, or estuary, and carry the sediments far out to sea.

Study Guide

1. Where is there more erosion, along a headland or inside a bay?
2. What is a sandbar called that is attached to the land?
3. Explain how a tombolo is formed.
4. In what kind of bays does the height of a tide wave increase?
5. Give a requirement for the formation of a delta.

SUMMARY

The relationship between the land and the ocean areas of the earth is changing constantly. The major changes are brought about when there are worldwide changes in sea level or continent-wide changes in land level. Emergent coasts have a coastal plain. Their shorelines are relatively regular. Submergent shorelines are irregular with headlands, bays, and islands. Marine terraces indicate how much the land-ocean relationship has changed.

The minor changes that occur where the land meets the sea are the result of wave and current action on sediments. Waves and currents build barrier beaches along an emergent coast. They build spits, bars, and tombolos along a submergent coast. In general, waves and currents smooth out the irregularities of submergent coasts, eroding the headlands and filling in the bays.

REVIEW AND DISCUSSION QUESTIONS

1. The coast of Texas is an emergent coast. What features would you expect to find on a map of that coast?
2. From New York harbor southward to Cape Lookout in North Carolina the river valleys are deeply invaded by the ocean, but at the same time there is a broad coastal plain. Explain what you think must have happened there.
3. It appears that in the United States both the southern Atlantic coast and the California coast are the result of uplift of the land. Why is it that one of these has a broad coastal plain and the other has not?
4. What features of the coastal plain of Georgia support the idea that the sea slowly retreated from the land there?

5. There is a broad arc of cuestas across northern Michigan and Ontario. What does this suggest to you?
6. The coast of Maine is very irregular, and there are many offshore islands. The exposed rocks of the region show signs of glaciation. Far out to sea lie the Grand Banks, which are composed of morainal material. From this information, develop a hypothesis to explain the Maine coast.
7. The sand that forms barrier beaches is piled up by waves. Explain how such beaches often have sand dunes and berms that are 10 feet or more above mean high tide.
8. Why do wave fronts approach a beach almost parallel to it?
9. Under what conditions can the energy from a broad wave front be concentrated on a narrower stretch of shoreline?
10. Under what conditions can the energy of a wave front be spread over a wider length of beach?
11. Occasionally a bar forms across the middle of a long, narrow bay. How would you account for that?
12. Collections of sand made along a beach often contain grains of minerals that must have been carried to the sea many miles away. How do you account for the longshore movement of these special grains?


ALVIN

CHAPTER 25

THE BOTTOM OF THE OCEAN

A very interesting feature of the earth's surface is the existence of two main levels: the average level of the continents, and more than two miles below that, the average level of the ocean bottom. Why do these two levels exist? Why is there not just one level? The ocean-bottom level is so much lower and broader than the continental level that the continents could easily disappear below sea level. After billions of years, why haven't they? Only recently have scientists started to answer this question.

Instruments have had to be invented to extend our senses so that we can detect what the sea floor is like. Vehicles have had to be invented to carry men closer to the sea floor. All these efforts are making the oceans more transparent to man's inspection.

25-1 CHARTING THE OCEAN BOTTOM

When we represent dry land on a sheet of paper, we call the result a **map**. The same sort of representation of the ocean is called a **chart**. Mapping the land is much easier than charting the ocean bottom. How easily could you draw a map of the land if you were in a balloon floating over the top of a solid layer of clouds?

Until the 1900's, charting oceans depended upon a length of rope or steel cable and a piece of lead. Seamen lowered a heavy lead weight on a piece of line to the bottom. The lead was smeared with a sticky fat, which held and brought back to the surface a sample of the bottom. The line was marked every fathom (6 feet, or about 2 meters) to measure the depth to which the lead weight had sunk.

In deep water this method is time-consuming and uncertain. The *Challenger* (1872–1876) and later vessels used a

The research vehicle *Alvin* of the Woods Hole Oceanographic Institution submerges to 6,000 feet.

With such lead lines, the main harbors of the world were charted. Away from these busy areas, little was known about the ocean floor.

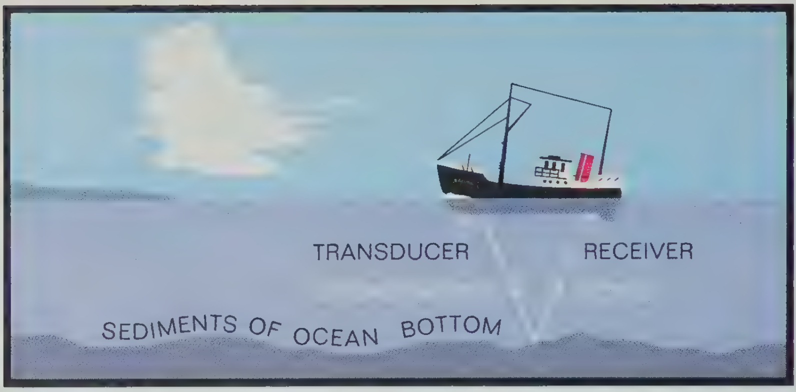


Figure 25-1 The transducer of the fathometer makes a sound, which bounces off the ocean bottom, and the hydrophone receives the echo.

long steel cable and a power hoist. Often the long cable or rope did not hang straight up and down because wind was blowing the ship or a current was carrying the line and the ship. A seaman could know how much line he let out, but he could not know whether that amount represented the true depth. This problem was overcome by a pressure-recording device attached to the cable. Pressure underwater is proportional to depth.

By the 1930's a rapid and accurate method of measuring the depth of the water under a vessel had been devised. This method depends upon the fact that sound travels through water, at the speed of 1,460 meters per second. A device called a **transducer** or **pinger**, on the bottom of a ship or towed behind it, makes a high-pitched noise, or "ping." The sound travels to the ocean bottom, and some of the sound energy reflects back to the vessel as an echo (see Figure 25-1). There it is received on a special listening device called a **hydrophone**. This method of sounding ocean depths is called **echo sounding**.

The sound and its echo from the bottom are recorded on a certain type of paper by an instrument called a **fathometer**. The time between the ping and the echo is measured with an accuracy of small fractions of a second. The time it takes for the sound to go to the bottom and back is recorded on the paper as a depth. Figure 25-2 shows a depth record. Continuous depth records of entire cruises are now made by many research and navy vessels. As a result, we are beginning to have the information needed to draw reasonably good charts of the ocean bottom.

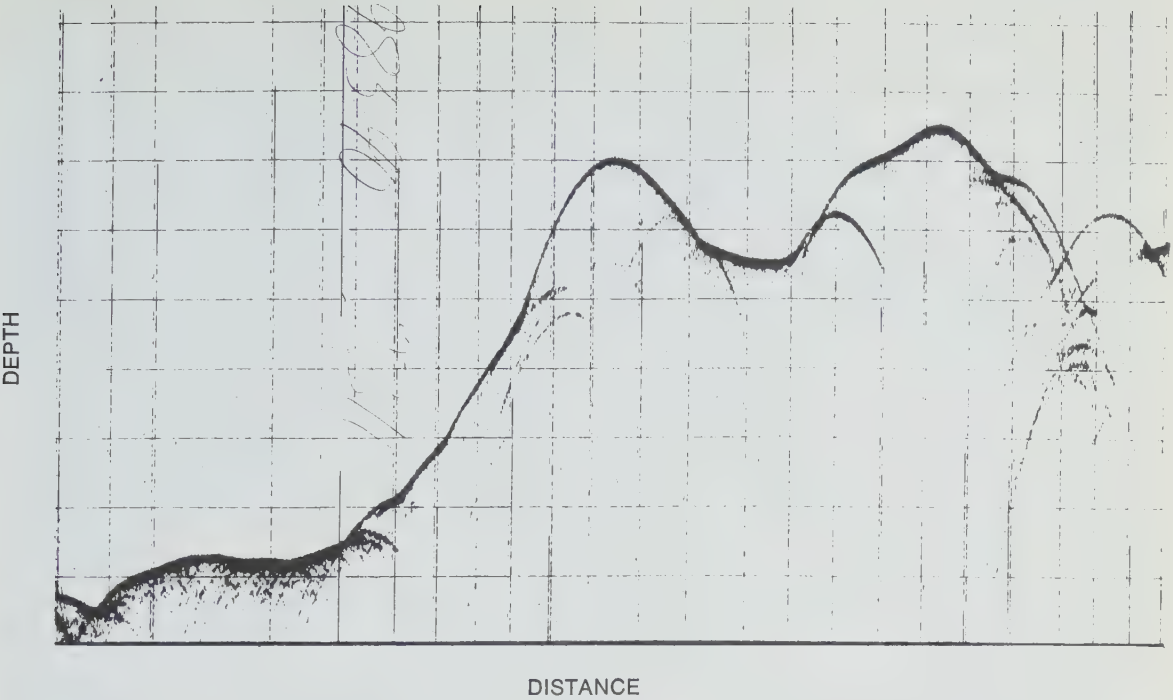


Figure 25-2 A fathometric record. The steepness of the slopes on the record depend not only on the slopes of the ocean bottom but also on the speed of the ship. Try to explain why this is so.

25-2 THE CONTINENTAL SHELF

Those of you who have visited the seashore have seen the uppermost edge of the ocean bottom. The continental shelf is the ocean bottom that extends outward from the shores of every continent.

Until 1946 the continental shelf was of little interest to anyone except oceanographers and fishermen. In that year the United States claimed the oil and other mineral resources that lie within the shelf along its coastlines. This meant there

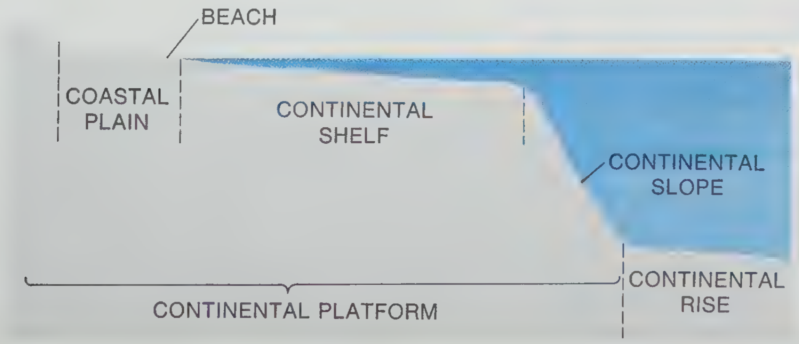


Figure 25-3 The continental shelf is the underwater border of a continent.

Figure 25-4 Much of the continental shelf is a broad, flat plain. Northeast of Cape Cod the shelf is as hilly as the dry land at the coast. Note how the continental shelf ends.

All previous national claims to parts of the ocean had been defined in distances from the coast—a three-mile line, for example.

was a need to define the term *continental shelf.* Legally, the shelf extends outward to the 600-foot depth line. The scientific definition of the continental shelf, however, is "the zone around the continents from the low-water line to the depth at which there is a marked increase in slope to a greater depth." Look at Figure 25-4 for details of the shelf.

The width of the shelf varies greatly. Off San Francisco, California, it is only about 30 miles wide. Along the East Coast, the continental shelf varies from about 260 miles in width off Boston, Massachusetts, to about 12 miles off Miami, Florida. Just as there is no set number of miles that the shelf

extends seaward from the land, there is also no set depth at which it ends. As a worldwide average, the continental shelf changes pitch, or slope, permanently at a depth of about 150 meters (490 feet).

A convenient way to express a pitch is to state it as an angle. A vertical canyon wall has an angle of 90 degrees. A steep ski slope might be 37 degrees. The surface of the continental shelf, however, has an average angle of pitch that is less than 1 degree. The average descent of the continental shelf is only about 10 feet per mile.

Let us look at an example. Off Barnegat, New Jersey, the outer edge of the shelf is 86 miles offshore, at a depth of 450 feet. What is the average slope in feet per mile? It is only 5.23 feet per mile. The ocean floor there would look flat and level.

25-3 THE MATERIAL ON THE CONTINENTAL SHELF

The surface of the continental shelf has been sampled from the first time that a seaman brought up sediment attached to his lead line. By now enough data has been accumulated to give us a reasonably good impression of the surface sediments. The most widespread are particles between 0.06 and 2.0 millimeters (0.002 and 0.05 inch) in diameter, which we call sand.

A hair or a piece of paper is about 0.003 inch thick.

There is also mud, which is a finer material than sand. Mud includes silt and clay. One way to determine whether a very fine sediment is mud or sand is to squeeze a handful into a mass and let it dry. If it easily falls apart when it is dry, the sediment is sand. If it holds together, it is mud. The least common of the shelf meterials is gravel, which varies in size from the largest sand grains to boulders over a foot in diameter.

The sand found on the shelf appears to have three different sources. The most common kind close to the coast is quartz grains from the land. The next most common kind of sand is formed by the action of waves breaking up shells and coral. In some places, such as southern Florida, these sands not only are on the shelf but also form the beaches. The third kind of sand is more common on the deeper part of the shelf. It is formed by chemical reactions that occur in sea water. Much of it is granular calcium carbonate, which has been precipitated from water.

The source of gravels, particularly the larger sizes, poses some problems. Gravels close to a rocky shore come from the

erosion of headlands, or cliffs, by waves. Those that are found far out to sea could not have been carried there by the deep action of waves or currents. Those forces are not strong enough at such depths. Some gravels may have been carried to their present location by streams during a period of lowered sea level. Others may have been carried by glaciers or icebergs.

25-4 FEATURES OF THE CONTINENTAL SHELF

It was formerly believed that the surface of the continental shelf was quite smooth. This is probably the reason that it was called a *shelf*. As sonic methods of sounding replaced the old lead line, more detailed information about the shelf was gathered. We now know that the surface of the shelf in the Gulf of Maine is as rugged as any hilly country on the land. Along the southern Atlantic Coast and the Gulf Coast there are extensive areas where the surface of the shelf appears to be relatively smooth. There it may be even flatter than the Great Plains.

It took a disaster to make us realize that the charts of sea bottom that we use are inadequate in most areas. In April 1963 the nuclear submarine *Thresher* sank in deep water off the coast of Massachusetts. Its battered hull now rests at a depth of 2,600 meters. The search for the hull produced thousands of echo-sounding depth measurements that, when plotted, produced a new chart of the sea bottom for that area.

The continental shelf off the Pacific Coast is very different from the shelf off the Atlantic Coast. It is composed of many basins and ridges—something like those off the Maine coast. At present our knowledge of the western shelf of North America is not so detailed or complete as that of the eastern shelf. This is being remedied rapidly by the oceanographic institutions of the West Coast and of the United States government.

There is an interesting structure off the coast of the southeastern states that appears to have no counterpart on the West Coast. This is the Blake Plateau. Figure 25-5 shows that it has a relatively smooth surface and lies seaward of the true continental shelf. Its surface is well below the level of the shelf but far above the true ocean floor. It appears to be a region of the continental shelf from which the Florida Current and the Gulf Stream have swept away sediments, thus preventing their accumulation over the past 25 to 30 million years.

Figure 25-5 The Blake Plateau, off the coast of Florida, may have been cleared of sediments by the deep waters of the Gulf Stream.

25-5 UNDERWATER CANYONS

Among the most puzzling features of the ocean bottom are the steep valleys that cut across the continental shelves. These are called **submarine canyons** because they compare in cross section with such gigantic formations as the Grand Canyon. In Figure 25-6 the submarine canyon off Monterey Bay, on the West Coast, is compared with the Grand Canyon. On the East Coast the Hudson River Canyon extends from the mouth of the Hudson River 80 miles across the shelf and down into the true ocean basin more than 2 miles deep. The Hatteras Canyon, off Chesapeake Bay, may be even greater.

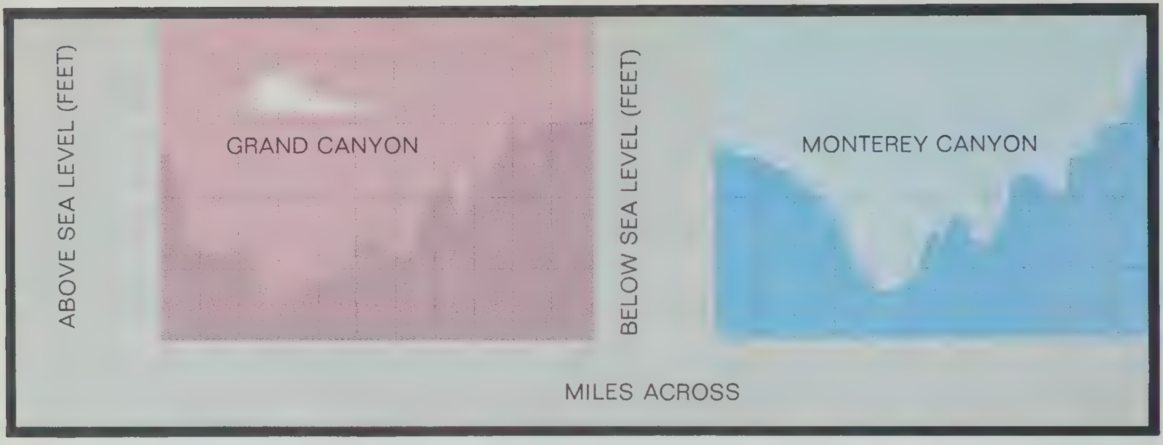


Figure 25-6 A comparison of the Grand Canyon with the Monterey Bay submarine canyon

When these canyons were first discovered, it was assumed that no erosion could occur underwater. Without underwater erosion, how could these canyons have been cut—if they were cut? This assumption made it necessary to believe the canyons were cut by rivers at a time when the present continental shelves may have stood several thousand feet above sea level. However, there is no acceptable way of accounting for such a great lowering of sea level. Some students of submarine canyons have suggested that a mixture of mud and water could slip down a slope as a current and erode the bottom, forming a canyon.

25-6 THE CONTINENTAL SLOPES

As we have defined the continental shelves, they extend at a gentle pitch outward from the land to the place where the sea floor begins to descend more steeply toward the true ocean bottom. The **continental slope** is this steeper edge of the shelf. What do we mean by *steeper*? We have seen that the average pitch of the shelves is less than 1 degree, or about 10 feet per mile. The continental slopes drop off a little more rapidly. Their average pitch is from 3 to 4 degrees, or about 300 feet per mile. This is a gentle pitch, but Figures 25-3 and 25-4 make it look steep because the vertical scale is not the same as the horizontal scale.

The continental slopes of the West Coast have a steeper-than-average pitch. Their pitch is about 528 feet per mile. Where the continental shelf is narrow, there is generally a comparatively steep continental slope.

The continental slope is not clearly marked off southern California. Instead, there is a broad region of islands, shallows, and deep basins. These features of the sea bottom are probably the result of vertical and horizontal movements of the earth's crust.

The continental slopes that have been charted are cut by huge canyons as deep as 4,000 feet. Some of these canyons are the continuations of canyons across the shelf. Most of them appear to be carved only in the slope. Dredge hauls from the slopes and the canyons have brought to the surface fossil-bearing sedimentary rocks. From the fossils in these rocks, it appears that the slopes are not very old. It is estimated that the sediments that formed the rocks were deposited during Late Cretaceous and Middle Tertiary time (100 million to 30 million years ago).

Study Guide

1. Explain the principle of the fathometer.
2. What is the earth scientist's definition of the continental shelf?
3. What is the average pitch of the continental shelf?
4. Name the three kinds of sand found on a shelf.
5. What seems to determine the topography of a given continental shelf?
6. What is a submarine canyon?
7. What is the average pitch of the continental slopes?

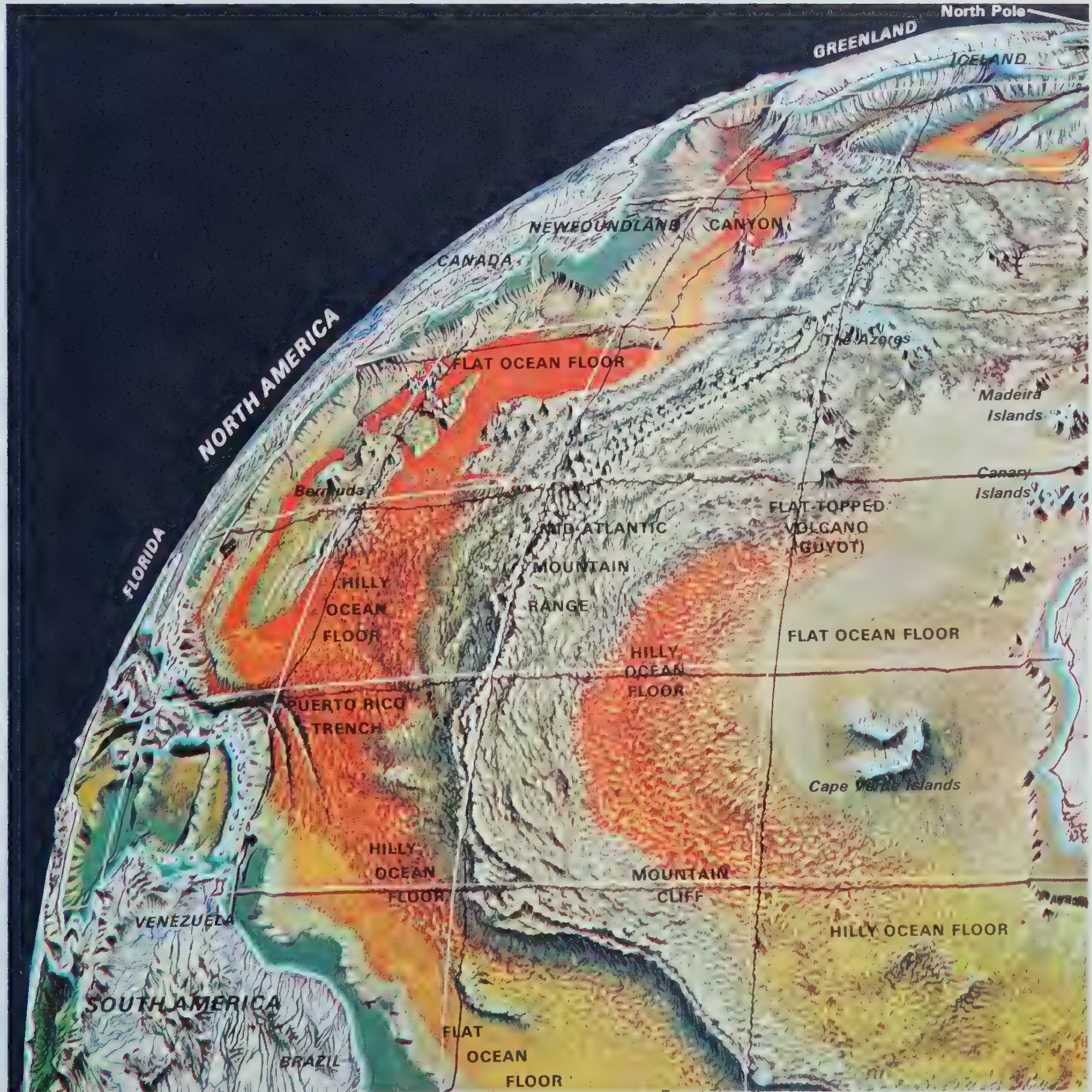
25-7 THE TRUE OCEAN BASINS

Several times we have mentioned the **true ocean basins**. These are the deep parts of the oceans, from which the continents rise. Before the voyage of the *Challenger* in the 1870's, nothing was known about these areas except that they were much more than 2,000 meters (6,000 feet) deep. They were imagined to be monotonously flat. The *Challenger* scientists discovered that the ocean basins had hilly and possibly mountainous sections, and that there were parts very much deeper than others. Now we know the average depth is 3.8 kilometers (2.4 miles).

Many nations have cooperated in charting parts of the ocean bottom by means of fathometers. Since a vessel records depths only along its course, most of what you see on a chart is guesswork. These charts show that the bottom of the oceans is as rugged as, or more rugged than, the surface of the continents (see Figures 25-7 and 25-8). Although there are some similarities among the oceans, each ocean has a characteristic system of structures.

Figure 25-7 The floor of the eastern half of the North Pacific Ocean

Figure 25-8 The floor of the western half of the North Atlantic Ocean



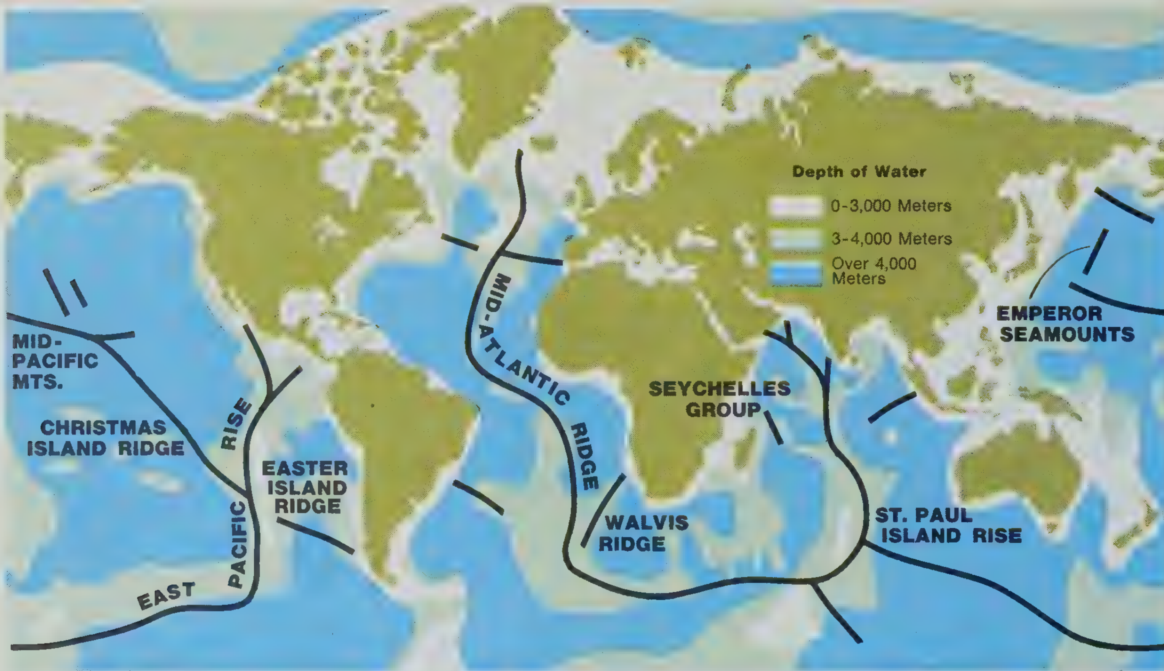


Figure 25-9 Mid-ocean ridges run through the ocean.

25-8 THE ATLANTIC'S MID-OCEAN RIDGE

Perhaps the most interesting feature of the Atlantic basin is the **mid-ocean ridge** extending the full length of the North and South Atlantic oceans. If, as some oceanographers believe, the Mid-Atlantic Ridge is only a section of the mid-ocean ridge that continues through all the oceans, it is part of a mountain range that is almost 64,000 kilometers (40,000 miles) long! Like the Rocky Mountains, the mid-ocean ridge is not a wholly connected, single range of mountains but a series of ranges that are almost connected. There appear to be gaps across the mid-ocean ridge. These might be similar to gaps across the Rocky Mountains. Figure 25-9 is a chart of ocean depths showing areas of the mid-ocean ridge.

The part of the mid-ocean ridge that lies in the North Atlantic Ocean is the best known. Individual peaks extend upward about 16,000 feet from the adjacent valley bottom. In one area in the middle of the ocean, the peaks break through the surface to form the volcanic islands called the Azores. Pico Island of the Azores rises 7,615 feet above sea level. This makes an underwater mountain range that compares with the Himalayas on the land.

The vicinity of the Mid-Atlantic Ridge is a region of earthquakes and volcanic activity. For example, Iceland, a portion of the ridge that is above the surface of the sea, is composed of volcanic rock. Surtsey, the new island that has appeared recently just south of Iceland, is being formed by volcanic action, as shown in Figure 25-10.

Some of the better-known parts of the Mid-Atlantic Ridge appear to be formed by two parallel ridges, which are separated by a very deep valley. To some geologists this valley resembles the great Rift Valley of Africa—deep depressions flanked by steep, high sides. Therefore, they call it the **Mid-Atlantic Rift**. The rocks that have been dredged from the flanks of the mid-ocean rift are basalt, a rock that is often found in association with volcanic action. The Rift Valley of Africa also has many volcanoes within it.

What has caused the mid-ocean ridge? On the continents, volcanoes appear to be associated with young and growing mountains. In such regions huge cracks occur in the crust of the earth. Through these cracks plastic rock sometimes oozes

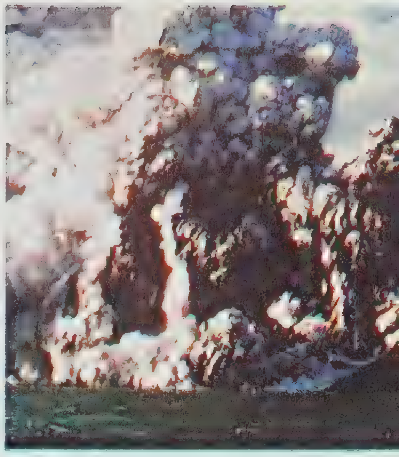


Figure 25-10 In November 1963, the ocean bottom off the coast of Iceland erupted and pushed up a volcano, now known as Surtsey Island.

ATLANTIC OCEAN

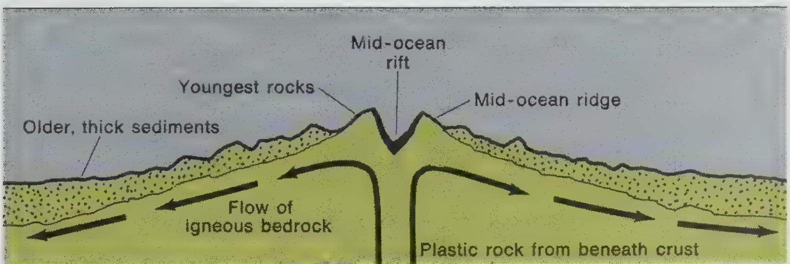


Figure 25-11 A section of the Mid-Atlantic Ridge

to the surface as a slow lava flow or explodes as a violent volcano. If the mid-ocean ridge is composed of material that has oozed upward through cracks, it is a system of cracks one hundred times as long as any we know on the continents.

The rocks that have been collected in the immediate vicinity of the ridge are relatively young, and some are modern — Surtsey, for example. Rocks from the hills that spread east and west from the ridge provide interesting evidence. They appear to be progessively older the more distant they are from the ridge (see Figure 32-2). The oldest of the rocks from this region of submarine hills have been tentatively dated as Early Tertiary.

The rocks closest to the ridge are youngest and those most distant are the oldest. This fact suggests that the ocean floor flanking the ridge has been pushed slowly away from the ridge as new material was brought to the surface. Such action would help to explain why the ocean basins appear to have been getting deeper since the Cretaceous Period. As material was extracted from beneath the ocean basins and piled up to form the hills of the mid-ocean ridge, the basins settled downward (see Section 32-3).

25-9 OTHER FEATURES OF THE ATLANTIC BASIN

On both sides of the North Atlantic, between the bottom of the continental slopes and the mid-ocean ridge, extensive areas of the sea bottom are almost flat. These are the **abyssal plains** — 5,000 to 6,000 meters (15,000 to 18,000 feet) below the ocean surface. Over much of their extent they appear to be as featureless as the great Staked Plain of Texas, without the gulleys that erosion has cut into the Texas plains. Here and there low, gently sloped hills rise 30 to 400 meters (100 to 1,200 feet) above the plains. Less frequently but much more conspicuously, isolated mountain peaks tower above the plains.

Off the coast of New England there is a line of underwater peaks called **seamounts**, which reach upward about 4,000 meters from the abyssal plains. This range of seamounts extends into the foot of the continental slope, called the **continental rise**. The bases of the westernmost seamounts appear to be buried by the continental rise. Off the coast of the Carolinas, seamounts rise so high that their tops just break the surface of the ocean. These are the Bermuda Islands, the upper portion of which is coral.

Figure 25-12 The base of the volcano on which the island of Bermuda rests is over 15,000 feet below sea level.

25-10 THE PACIFIC BASIN

In the Pacific Ocean, there are great gashes in the sea bottom, called **trenches** or **troughs**. They are long and narrow, and extend downward to great depths. The walls of these structures are steep. Figure 25-13 shows that a trench appears to be associated with a group of islands.

Figure 25-13 A deep trench is often located beside a group of islands called an island arc.

The longest of the Pacific trenches is in the South Pacific Ocean, bordering close upon the coast of South America. There the east wall of the trench is almost continuous with the west flank of the Andes Mountains. The combined difference in elevation of the earth's crust from the bottom of the Chile-Peru Trench to the summit of the Andes is about 14 kilometers (close to 9 miles)!

The deepest water in all the oceans is found in the Mariana Trench in the eastern Pacific. There the floor of the Challenger Deep lies about 12 kilometers below sea level. In January 1960, the deep-sea vessel *Trieste*, piloted by Jacques Picard for the United States Navy, made a successful dive to the bottom of that awesome trench in the earth's surface.

Extending westward from our Pacific Coast there is another set of features that may be rare in the Atlantic Ocean bottom. In Figure 25-7, you can see a series of four more-or-less parallel east-west fracture zones that extend as far west as the Hawaiian Islands. Along each of these fracture zones the crust of the earth has been displaced upward or downward, forming a long line of submarine cliffs, or **escarpments**, about 1,000 meters high (see Figure 25-14).

Although there are only a few dozen known seamounts in the North Atlantic Ocean, the North Pacific Ocean contains hundreds of them. Some of the seamounts in the Pacific and a few in the Atlantic are peculiar because they have flat tops. These flat-topped seamounts are called **guyots**, in honor of a French geographer.

guyot (GEE oh)

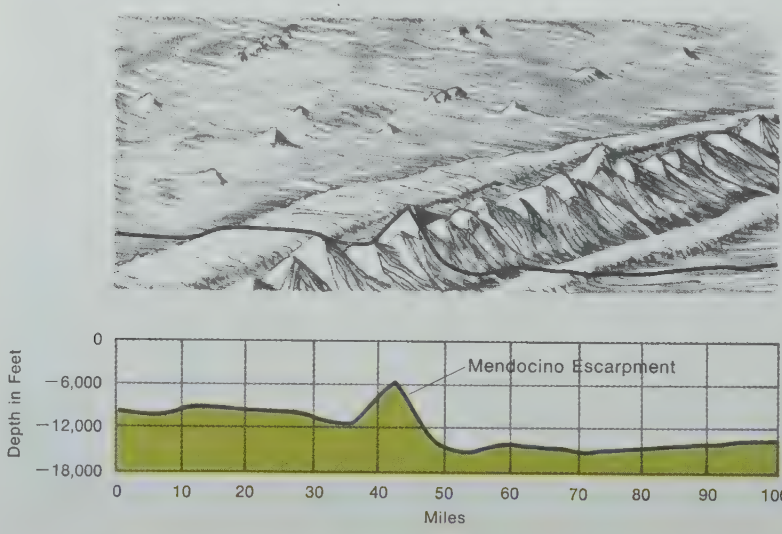


Figure 25-14 The fracture zones in the eastern part of the North Pacific Ocean may extend into the Pacific Coast of North America.

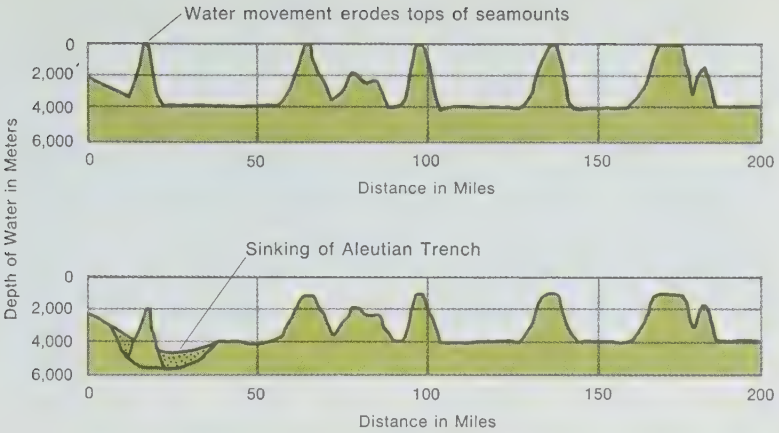


Figure 25-15 The flat tops of guyots may have been formed by surface wave action when the tops of the seamounts were at or above sea level.

The best explanation for these structures is that they were once seamounts. At one time their tops reached close enough to the surface of the ocean to be affected by great ocean waves (see Figure 25-15). It is suggested that wave action washed away the loose volcanic material that composed the top of the seamount, leaving a flat top. The tops of many, if not most, guyots are now so far below the surface that even the greatest ocean waves do not disturb them.

We do not know whether much more water has entered the oceans since the waves planed the tops of these submarine mountains, or whether the bottom of the ocean has sunk. Probably a combination of events took place.

At least one bit of evidence supports the theory of ocean-bottom settling. A series of seamounts that have their tops about equal distance below the surface has its end member in the Aleutian Trench. The top of that seamount lies much deeper below the surface than do the tops of the others in the series.

25-11 DEEP-SEA SEDIMENTS

The study of cores of sediments from the true ocean basins has increased our understanding of sedimentation. Before World War II, only four expeditions raised cores as long as 10 feet from the deeper parts of the ocean basins. During World War II, Borje Kullenberg, of the Swedish Oceanographic Institute, invented the piston corer that is now used. With it, cores as long as 80 feet have been raised (see Figure 25-16).

Old-fashioned bottom sampling had shown that different parts of the deep sea contained different kinds of sediments.

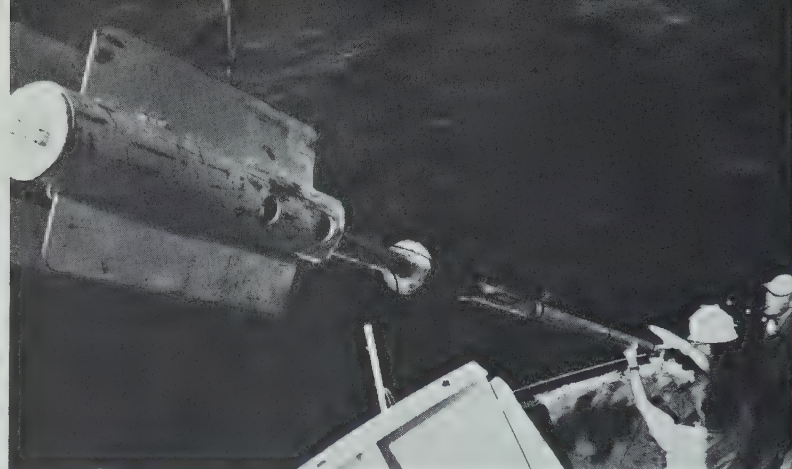


Figure 25-16 A piston corer plunges into the ocean floor and retrieves a core of the sediments.

Modern deep coring has confirmed these earlier discoveries and has also shown that the sediments of the deep sea are stratified and varied. The combination of deep coring and radioactive dating tells us that the rate of deposition is very slow in the deep ocean. It is estimated that only about 1 millimeter to 1 centimeter (0.04 to 0.4 inch) of material is deposited in 1,000 years in those parts of the ocean farthest from land.

Study Guide

1. What is the outstanding characteristic of the Atlantic Ocean basin?
2. What is a rift valley?
3. Explain what may have caused the mid-ocean ridge.
4. Do the ocean basins seem to be getting deeper, or shallower?
5. Name three characteristic features of the Pacific Ocean basin.
6. What is a fracture zone?
7. How does a seamount differ from a guyot?
8. What does the term *rate of deposition* mean?

SUMMARY

The coastal plains of the land extend under the sea as continental shelves. These are generally flat and gently sloping fringes of the continent. The shelves of the East Coast are generally wider than those of the West Coast. The topography of the shelf is often similar to that of the land next to it. A few submarine canyons leading from river valleys cross the shelves and plunge down the continental slope to the true ocean bottom. The seaward edge of the shelves drops down at an angle of only 3 to 4 degrees. In some areas only the continental slope is cut by canyons.

By using the many records of fathometers, areas of the ocean have been charted in fair detail. The ocean basins are as diverse as the surface of the continents. The Mid-Atlantic Ridge runs the

length of the Atlantic Ocean and may extend even farther. The ridge is an area of volcanic activity. From the abyssal plains tower isolated seamounts. The tops of some seamounts in the Pacific have been planed off by wave action. The Pacific basin contains east-west fracture-zone escarpments.

REVIEW AND DISCUSSION QUESTIONS

1. Compare mapping the land with charting the topography of the ocean bottom.
2. The pressure-depth gauge measures depth because a gas responds to pressure. If the pressure is doubled, the volume of a confined gas is reduced to one half. The pressure at a depth of 30 feet compresses the gas filling a tube 100 cm long to 50 cm. How much of the tube will be filled with gas at a depth of 120 feet?
3. Explain the principle of the fathometer.
4. How long does it take a fathometer to record an ocean depth of 10,000 meters? of 10,000 feet?
5. The distance from the fall line to the outer edge of the continental shelf is about the same from Georgia to Nova Scotia. From the information you learned in Chapter 24, describe the width of the continental shelf from Georgia to Nova Scotia.
6. How does the pitch of the continental slope compare with the pitch of a mountain?
7. On a piece of graph paper, redraw Figure 25-6 with the vertical scale the same as the horizontal scale.
8. Where the Hudson River Canyon enters the continental slope, dredges have brought fossils of land life to the surface. How does this fact support one of the theories about the formation of the canyon?
9. Why does material not wash down from underwater ridges and hills and fill the ocean basins and trenches?
10. There is a row of seamounts in the true ocean bottom east-southeast of Cape Cod. The westernmost of these seamounts is partly buried in the continental slope. What does this fact tell you about the continental slope?
11. Where have scientists found the youngest rocks built up from the ocean floor?
12. Why are oceanographic geologists particularly interested in the mid-ocean ridge?
13. On a piece of paper, draw what you believe a fathometer would record as it passes over a guyot; as it passes over a submarine cliff, or fracture-zone escarpment.
14. What evidence have you studied that makes it unwise to believe the shapes and sizes of continents never change?

CHAPTER **26**

MOUNTAINS FROM THE OCEAN

For more than 200 years, geologists have been studying marine sediments exposed on the land. Long ago these sediments accumulated on the sea bottom and slowly turned to sedimentary rock. It was this kind of rock that James Hutton was interested in. In it William Smith found the fossils on which he based his geologic column. Some of the rocks appeared to have been lifted from the oceans without much change. Others appeared to have been folded into huge wrinkles to form mountains. It was not until the last century that geologists began to understand how these sedimentary rocks may have attained such great thickness. Then they began to understand how they may have been folded in such a way as to form mountains.

26-1 JAMES HALL AND THE ROGERS BROTHERS

The man who taught us most about the sedimentary rocks in the eastern part of the United States was James Hall (see Figure 26-1). In 1836, Hall was hired as an assistant in geology by the newly formed Natural History Survey of New York. He was soon assigned to work in the western part of the state. To most geologists, the layer upon layer of sedimentary rocks found in western New York were uninteresting and unimportant. However, Hall was challenged by his assignment. He found the rocks fascinating because of the many fossils they contained. He spent most of the next sixty years of his life studying areas like that shown in Figure 26-2.

What Hall learned about the fossils and sedimentary rocks of western New York State confirmed what Sedgwick and Murchison had found in Europe (see Section 7-1). American fossils followed the same sequence as European fossils. Because of this, Hall started a practice that geologists still use. He gave the same names to the geological periods as those used in Europe.

Folded mountains of the Appalachians, with the Juniata River in the foreground

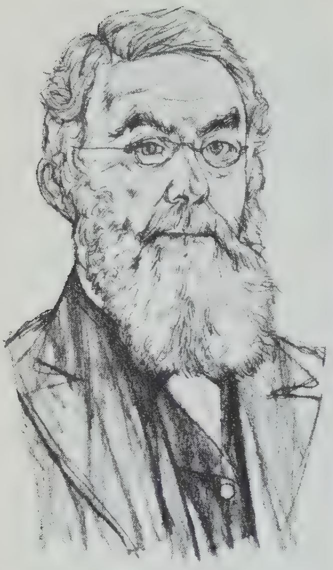


Figure 26-1 James Hall (American, 1811–1898) explored the beaches and forests around his home in Hingham, Massachusetts. After learning all the science the village school offered, he attended Rensselaer Polytechnic Institute at Troy, New York. Hall's family was too poor to pay for his transportation, so he walked the 250 miles to college.

Figure 26-2 Sedimentary outcrop of the Genesee River gorge in New York

While Hall was working in New York, Henry Rogers and William Rogers, sons of a well-to-do doctor in Philadelphia, started to study the mountains of Pennsylvania and Virginia. They eventually came to the conclusion that these mountains had been carved by rivers from huge folds of sedimentary rock. The work done by them and by Hall forms the basis of our modern knowledge of the Appalachians and all other folded mountains.

26-2 WHEN WERE THE APPALACHIANS FORMED FROM SEA-BOTTOM SEDIMENTS?

The fossils that Hall found in the sediments of the Appalachians were clues to the ages of the rocks. The oldest (bottom-most) sediments had accumulated during the early part of the Paleozoic Era—the Cambrian Period. Near the surface are rocks of the Carboniferous Period. Between these two periods, enough sediments accumulated to produce a mass of sedimentary rock that is now at least 9,000 meters (30,000 feet) thick in some parts of Pennsylvania. This great thickness has been estimated by adding together the thicknesses of various rock formations exposed in folds. We do not

know how much has been eroded away. However, the original sediments that produced this pile of rocks must once have been at least 15,000 meters thick.

Hall studied these ancient fossil-bearing rocks from the Atlantic Coast to the Midwest. He found them to be thickest in the heart of the mountain country and to become thinner toward the west and the east. In 1859, Hall conceived the idea that the sediments had accumulated on the bottom of a deep depression in the floor of the ocean. A few years later, James Dwight Dana, a famous mineralogist and geologist at Yale University, named such a giant depression a **geosyncline**.

geosyncline (jee oh SIN klyn).

26-3 HOW SEDIMENTARY ROCK CAN BE FIVE MILES THICK

Hall thought the deep depression had always existed. We now believe the weight of the sediments caused the depression.

It was not until the 1930's that geologists all over the world had gathered enough information to realize that Hall's idea was a good one. In 1936, Marshall Kay of Columbia University put together evidence from many sources and proposed a hypothesis to explain Hall's original observations. To understand Kay's hypothesis, we, too, will have to study some of that evidence.

The evidence comes from fossils and from rocks. Oceanographers have shown us that there is very little life in the deep abyss of the sea. Most bottom life is confined to the shallow water of the continental shelf—water less than 200 meters (600 feet) deep. This fact leads us to believe the fossils Hall found in the Paleozoic rocks had lived in shallow water—no matter how deeply buried they are today.

There is only one acceptable way to explain what happened. The fossil record suggests that the surface of the sediments was never far below the surface of the ocean. The great thickness of the sedimentary rocks can be explained if we assume one factor. As the sediments accumulated, their great weight depressed the earth's crust beneath them. This would produce the geosyncline that Hall had theorized.

When we examine the rocks of the Appalachians, it is evident that we can divide the system into two parts, as shown in Figure 26-3. The eastern part is the mountains that face the Atlantic Ocean. These are largely composed of metamorphosed sediments (see Section 5-9). The original sediments appear to have been a mixture of volcanic material, sand, and clay. The western part of the system overlooks the Mississippi Valley. It is composed of sedimentary rock—limestones, sandstones, and some shales.

Figure 26-3 In the Appalachian system, sedimentary rocks form the western flank of the mountains, and metamorphic and igneous rocks form the eastern flank.

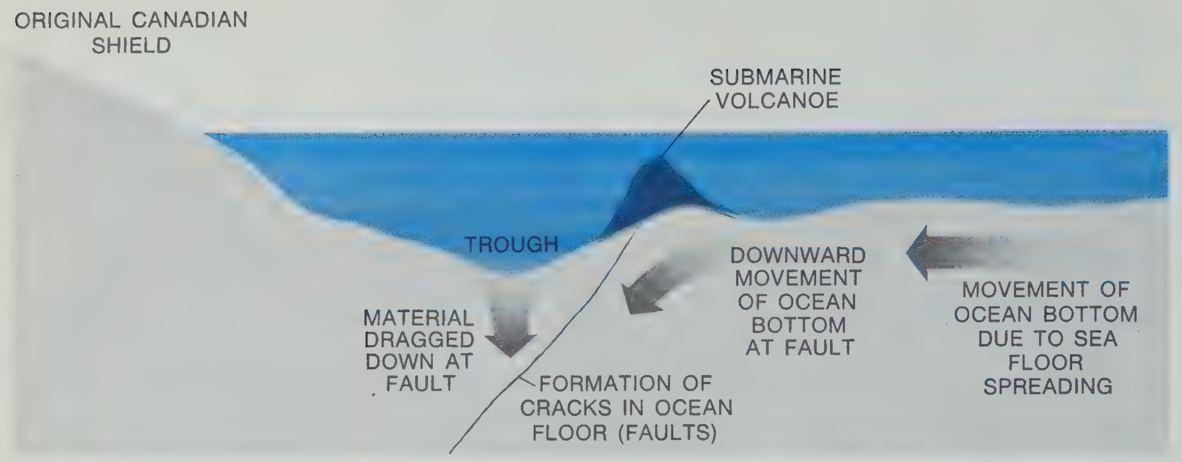


Figure 26-4 Formation of a geosyncline. Offshore from the continent a zone of weakness forms and erupts, producing submarine volcanoes with troughs on either side.

Study Guide

1. Why do we find so few fossils in sedimentary rocks that formed on the abyssal plains of the oceans?
2. What similarities are there between the fossils of Europe and those of North America?
3. What is a geosyncline?
4. How deep was the water in which the fossils Hall studied were formed? How do we know?
5. Why was Kay's explanation of the geosyncline a logical one?

26-4 WHAT HAPPENED?

Hall did not explain what caused this weak zone. A new hypothesis is that it may have been caused by the spreading of the ocean floor.

Kay's explanation of the formation of the Appalachians seems to be reasonable. It has not been proved, but it is a working hypothesis that geologists use. First, a zone of weakness developed in the sea bottom off the original coast. In this weakened zone a series of deep cracks developed, from which poured billions and billions of tons of volcanic material (see Figure 26-4). The removal of so much material from beneath the crust further weakened it, and the weak zone grew wider. It spread to both sides of the volcanic cracks as material was removed from underneath. The sea bottom may have gradually sunk near the **fault**, or crack, to form two troughs with a long line of volcanic islands between them.

Today there are several chains of volcanic islands flanked by troughs in the ocean bottom. Each of these formations, called an **island arc**, has a deep trench on its ocean side and a shallower depression between the arc and the continent (see Figure 26-5). The islands of Japan and the Aleutian Islands, both bordering the Pacific Ocean, are almost perfect examples of the systems Kay described.

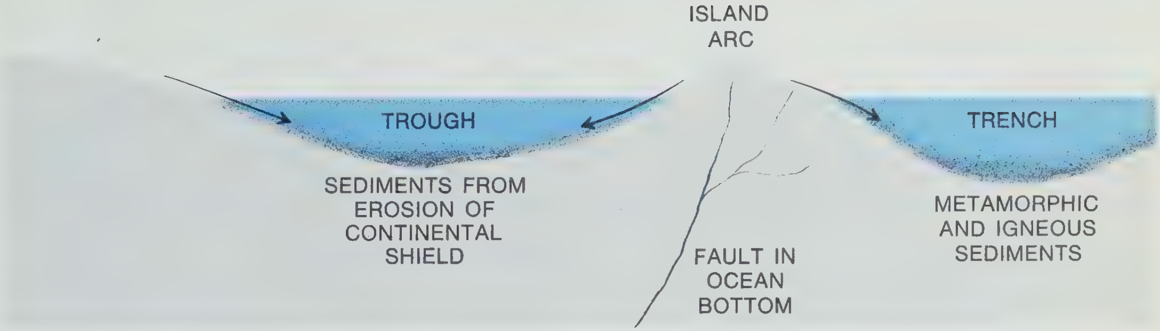


Figure 26-5 The zone of weakness becomes an offshore island arc with a trench on the ocean side and a trough on the continental side.

The second part of Kay's theory of the formation of the Appalachians is that sediments accumulated alongside the volcanic islands. The debris that settled in the outer trench was almost entirely of volcanic origin. The sediments that formed in the shallow sea on the landward side came from the continent. Near the islands they may have contained some volcanic material. Look at Figure 26-5 again.

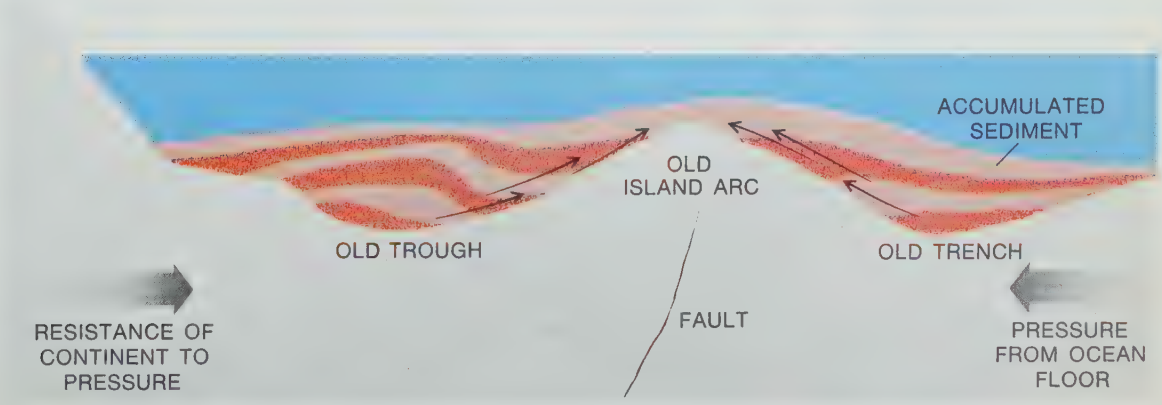
As more and more sediment accumulated in the shallow sea, the weight depressed the underlying crust. What once had been deposited in a shallow portion of the ocean was buried, and settled deeper and deeper into the forming geosyncline.

The third part of Kay's geosyncline theory is that some force began to exert pressure on the sides of the troughs (see Figure 26-6). We are not certain what that force was, nor do we know the source of its enormous energy.

In the case of the Appalachians, the trench on the ocean side of the island arc was the first to be squeezed. As the

When we learn how to drill and recover very long cores from the ocean floor, we may find evidence to support this second step of Kay's hypothesis.

Figure 26-6 Lateral pressure is responsible for the uplifting and folding of the geosyncline.



walls of the trench were forced closer together, some of the material within the trench was converted to metamorphic rock and forced upward. This rock emerged from the sea and became new land. The rugged country of the Maritime Provinces of Canada and much of New England has been carved from the land formed that way.

The sediments to the west of the island arc were also uplifted. Only in a few cases were these sedimentary rocks metamorphosed. Apparently, the pressure and heat for that uplift was not so great as in the outer region. However, it was sufficient to fold the once-almost-horizontal strata much as a piece of corrugated cardboard is folded.

This folding took place very slowly—perhaps over a period of 100 million years. Figure 26-6 shows how it may have occurred. During that time, the exposed land was already being eroded by streams. Great fans of eroded material, called **clastic wedges**, were spread far into a shallow sea that occupied much of what is now the Mississippi Valley (see Figure 26-3). The first of these fans was built during the Late Ordovician Period, and spread across northern New York State.

26-5 THE APPALACHIANS TODAY

The Appalachian Mountains that we see today are the result of several hundred million years of work by streams upon the rocks. This is enough time to have eroded all the land to base level. Theoretically, there should be no Appalachian Mountains, but there are. The picture at the beginning of this chapter is a view of a part of the present mountain system. Careful study of these mountains has supplied a few clues to what has happened.

The strata of folded sedimentary rocks do not offer uniform resistance to erosion. The individual mountains we see today are the remains of the most resistant rocks. In some cases, these mountains have been formed from the upward rounded parts of a fold. Such mountains are called **anticlinal mountains**, from the term **anticline** used for such an upward fold. **Synclinal mountains** have been formed from downward folds, called **synclines**. Figure 26-7 shows the formation of these folds. Over large areas, the summits of ranges of both anticlinal and synclinal mountains are often at about the same elevation above sea level (see Figure 26-8). An anticlinal mountain is shown in Figure 26-9.

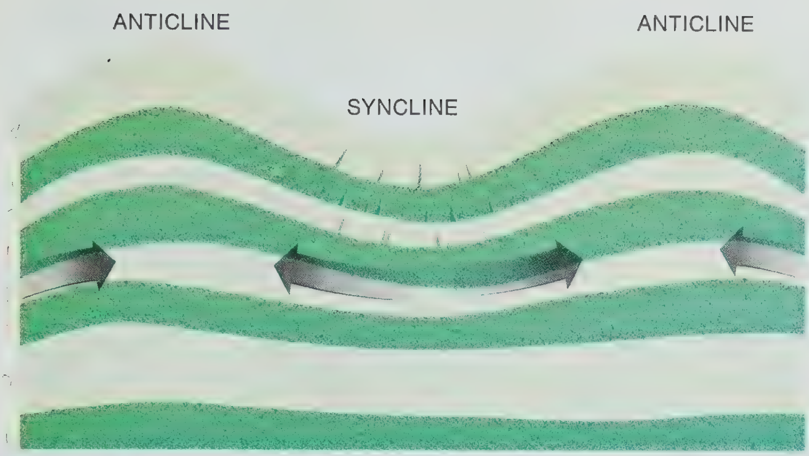


Figure 26-7 The formation of synclinal mountains depends on lateral pressure and eventual erosion of layers of soft rock.

peneplain (PEEN uh playn); Latin: *pene*, almost + plain.

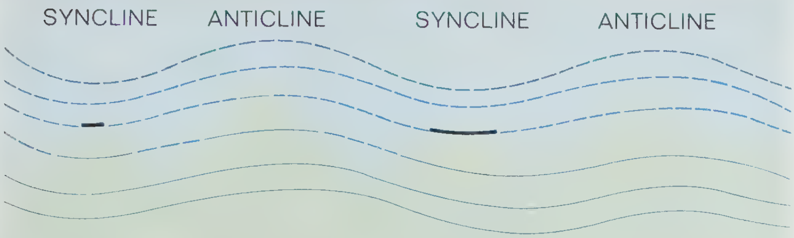


Figure 26-8 A range of anticlinal and synclinal mountains of about the same elevation. The dashed lines indicate the original shape and height of these folded mountains.

Figure 26-9 Sheep Mountain in Wyoming is an anticlinal mountain located where forests do not obscure its structure. In forested areas like the Appalachians it is difficult to see the structure of the land.

The uniform height of the summits suggests that at one time in the past the whole region had been eroded to an almost flat plain, only to be uplifted and carved again by streams. Such reduction of a region to a surface that is almost a plain is called **peneplanation**. The region itself is called a **peneplain**. Occasionally, a particular area of rock is extremely resistant to erosion and will remain sticking up out of the flat plain. Such an isolated hill or mountain is called a **monadnock** (see Figure 26-10).

If a peneplain is uplifted, the streams' gradients increase, and the area is said to be **rejuvenated**. Old, slow-moving streams with little eroding power will become swift-moving streams with great eroding power. When this happens, streams will cut away the softer rock and leave the more resistant rock standing as mountains. Because the tops of these mountains were once part of a level peneplain, they all are about the same elevation above sea level.

Figure 26-10 Stone Mountain in Georgia is an example of a monadnock. The region surrounding the mountain has been eroded down to an almost level plain.

Figure 26-11 Small synclines and anticlines may be seen in road cuts.

Study Guide

1. What would happen to the surface of the earth's crust in areas near continuous volcanic activity?
2. Where in respect to an island arc would fossils most likely be preserved? Why?
3. Why can we not yet fully test the geosyncline theory of mountain building?
4. From what direction were the forces coming that uplifted the Appalachian island arc? How do we know?
5. Why are most of the present Appalachian Mountains the same height?

26-6 STREAMS IN THE MOUNTAINS

Rejuvenation affects streams. Those streams that cannot erode their beds as fast as the land is uplifted become dammed by the rising land. The water becomes trapped behind the natural dam until it overflows into a new course. The old course of the river may remain at the summit of the ridge as a **wind gap**, as shown in Figure 26-12.

The streams that are powerful enough to erode their beds as fast as the land is being uplifted can maintain their old courses. These streams cut deep notches, or **water gaps**, through the uplifted hard strata. Figure 26-12 also shows how

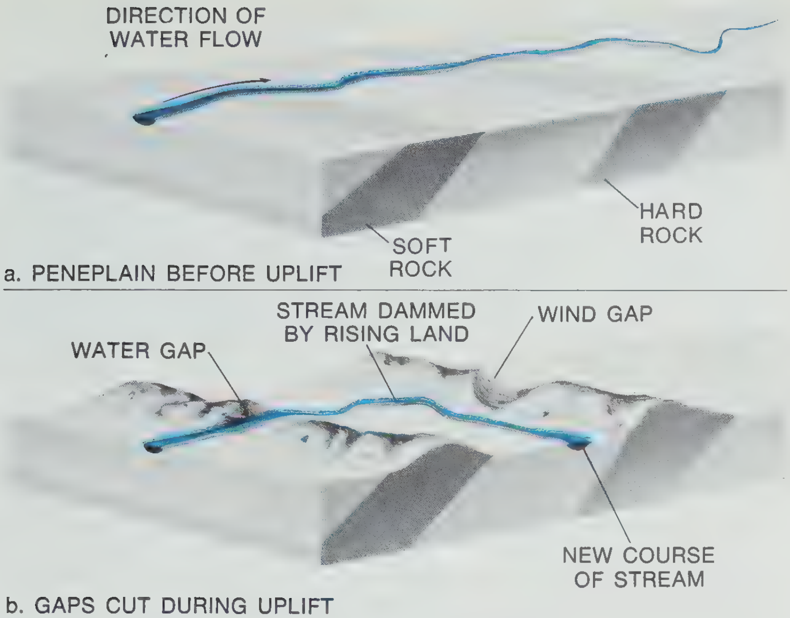


Figure 26-12 A water gap is formed when the erosion of a stream keeps up with mountain formation. A wind gap is formed when the erosion of a stream cannot keep up with mountain formation, and the stream makes a new course parallel to the mountain. The wind gap is the old, raised stream bed.

a water gap forms. There are many such water and wind gaps throughout the Appalachian Mountains.

The great ridges of the present Appalachians are not the remains of the original mountains, but what is left after erosion. It seems probable that the Appalachian Mountains have been reduced to a peneplain several times in their long history. Each time that happened, it was followed by uplift of the land and rejuvenation of the streams. Then a new cycle of erosion commenced.

The early settlers of the Midwest found their way to the open lands through the Cumberland Gap, a wind gap in Tennessee.

We do not know how long it takes to go through a cycle from one peneplain stage to the next—perhaps 50 to 100 million years.

26-7 HOW DO WE EXPLAIN REPEATED UPLIFTS?

The usual explanation for the original uplift that formed the Appalachians from sea-bottom sediments is that lateral pressure was exerted on them. Can we use the same explanation for the more recent uplifts? If we do, we should expect each uplift to result in additional folding and squeezing of the region into a smaller space. There is little or no evidence of this in the Appalachian region, so we must look for another explanation.

In Section 21-5 you learned that uplift and depression of the land can be the result of isostasy, the balancing of the weight of the earth's crust. Let us see whether this idea can be used to explain a series of uplifts and peneplanations like those that may have taken place in the Appalachians.

Figure 26-13 As a person goes up and away from the earth's surface, the force that gravity exerts on him decreases.

To use isostasy as an explanation, we must account for the removal of mass (rock) from one region and its transfer to another. This is precisely what streams do, and there are many streams in the Appalachians. They flow from the region where they are eroding the mountains to the adjacent areas where they deposit alluvium. So far our idea seems to be a good one. Is there any way we can gather evidence that will support or refute this idea? There is one way that involves the measurement of the force of gravity. To see why this is important, we will have to leave the Appalachians and our problem for a few pages.

26-8 MEASURING THE FORCE OF GRAVITY

Every time you step on a spring scale to measure your weight, what do you really measure? You measure the local effect of gravity on your mass. This effect is related to your mass, the mass of the earth, and the distance between you and the center of gravity of the earth (see Section 2-3).

It is because of such relationships that you would *weigh* less on the moon. Your *mass* is the same on the earth or the moon, but the mass of the moon is only 1/80 that of the earth. However, your *weight* would not be only 1/80 as heavy on the moon. Why? The moon's radius is only about 1/4 as great as the earth's. Therefore, you would be much closer to the center of gravity on the moon than you are on the earth. As a result, without change in mass, you would weigh on the moon about 17 percent of what you weigh on the earth. (g on the moon is about 1.6 meters/sec/sec.) This relationship is shown in Figure 26-13.

How can gravity be used to help us with our problem about the Appalachians? In 1735, Pierre Bouguer, a French mathematician, was on an expedition to Ecuador, in the Andes of South America. He made a discovery that gave geologists a new tool. He was using a pendulum clock to measure the time needed for astronomic observations. His clock was an excellent timekeeper at sea level. He discovered, however, that it ran a little slow at Quito, Ecuador, which is about 2,900 meters (9,400 feet) above sea level. When he carried the clock to the top of nearby Mount Pichincha, which is about 4,800 meters (15,700 feet) high, his clock ran even slower.

Bouguer thought about this strange effect. He reasoned that the higher he climbed above sea level, the farther he

was from the center of the earth. This caused the force of gravity to decrease and have less effect on the pendulum of his clock.

Study Guide

1. What factors control the path a stream will follow in the Appalachians?
2. How is the formation of a water gap different from that of a wind gap?
3. How is a monadnock formed?
4. Why would you weigh less on the top of a high mountain than at sea level?
5. How did Bouguer discover that the force of gravity is not uniform on the earth's surface?

26-9 THE DIFFERENCE BETWEEN THEORY AND FACT

Further measurements by Bouguer and other scientists have taught us that the force of gravity is not uniform on the earth's surface. In addition to varying with altitude above sea level, it varies with latitude. At sea level, the farther you go from the equator, the greater is the force of gravity, because the earth is not a true sphere.

From the measurements made with pendulums, earth scientists precisely predicted what the force of gravity *should* be anywhere on the surface of the earth. The next thing to do, of course, was to see whether these predictions were correct. They were not! The scientists could not decide what was wrong. Maybe their idea of the earth's structure was wrong.

An old idea in geology was that if it were possible to drill cores to the center of the earth, every core removed would have the same mass. Since we cannot do this, and since we do not know very much about the interior of the earth, perhaps that idea is wrong. How can we change the idea to explain the difference between the *theoretical* force of gravity and the *observed* force? This difference is called the **Bouguer anomaly**.

We know from observation that at the surface the rocks vary in density (mass per unit of volume). We know that sedimentary rocks are less dense than most igneous rocks. We also know that sedimentary rocks are spread unevenly in area and in depth on the surface of the earth. All these facts are clues to why there must be a Bouguer anomaly in many places.

Suppose we assume that from the center of the earth *almost* to its surface the distribution of mass is uniform. Then all we need to think about is the crust, the outer 16 to 40 kilometers (10 to 25 miles). Above a region where a column of rocks from the surface to the center of the earth has a little less mass than the average, the force of gravity will be a *little less than average*. Such a condition is called a *negative* Bouguer anomaly. Where the reverse is true, the anomaly is *positive*. Measurements of the Bouguer anomaly have been made in many places. One is shown for Colorado Springs in the following calculations.

Colorado Springs *(Latitude: 38° 50.7′N; Altitude: 1,814 meters)*

Standard gravity for this latitude	980.076 cm/sec^2
Correction for altitude	− 0.561
Theoretical gravity	979.515
Measured gravity	979.490
Gravity anomaly *(difference between theoretical and measured)*	− 0.025 cm/sec^2

Therefore, the underlying rock in this region must have less mass than average.

A Dutch geophysicist, F. A. Vening-Meinesz, discovered how to make measurements of the force of gravity at sea. He installed a gravity pendulum in a submarine, which provides, below the surface, the steady platform necessary for gravity measurements.

In general, the anomaly is negative in mountain areas, where erosion is going on (see Figure 21-1). When mountains are first formed, the gravity anomaly is zero. As soon as some material is removed by erosion, the mountains become lighter, and the gravity anomaly is negative.

One of the most important gravity discoveries is that over every trench in the oceans (see Section 25-10) there is a negative Bouguer anomaly. This means that the earth's crust in the region of a trench is out of balance with the adjacent crust. The result of this lack of balance in the crust may force the walls of the trench together and squeeze the contained sediments upward to form an island arc (see Section 26-4).

26-10 ISOSTASY AND THE BOUGUER ANOMALY IN THE APPALACHIANS

The Appalachians are a great mass of sedimentary rock that we believe is embedded in crystalline rock. The sedimentary rock has a density of about 2.4 grams per cubic centimeter. The crystalline rock has a density of about 3.0 grams per cubic centimeter. Does the less dense sedimentary rock have

any effect on the denser crystalline rock below it? We can get some idea of an answer to that question by performing a mental experiment.

Let us imagine a block of wood with a density of 0.8 gram per cubic centimeter floating in water (density 1.0 gram per cubic centimeter). Does the block float on top of the water? No. Most of the block is below the level of the water (see Figure 26-14a). Only a small portion of the floating wooden block extends above the level of the water.

The sedimentary rocks of the Appalachians act like the block of wood. We can consider that the lower-density sedimentary rock of the Appalachians presses into the denser crystalline rock beneath it. Then only a small portion of the sedimentary rock extends above the level of the crystalline rock. The rest is buried in it, just as the major part of the wooden block is buried in the water (see Figure 26-15).

If our wooden block is 10 centimeters thick, it will float with 8 centimeters below the level of the water and 2 centimeters above the level of the water. Why? Suppose we cut off the 2 centimeters of the block that is above water. Will it now float with the top exactly at the water level? No. As shown in Figure 26-14b, it will still float with part of its thickness out of the water.

Let us apply to the Appalachians what we have learned from this mental experiment. We can compare the steps in a table of equivalent actions.

Wood-block experiment	*Appalachian Mountains*
1. The original block is floating in water.	1. The sedimentary rock is "floating" in the crystalline rock (zero Bouguer anomaly).
2. We cut off the part of the block that is above water.	2. The mountains are peneplained (negative Bouguer anomaly results).
3. Buoyancy raises the block, so it floats partly above water.	3. Buoyancy uplifts the region (zero Bouguer anomaly is regained).

We could repeat reducing the thickness of the wooden block many times. Each time the block would again float with part of its thickness out of water. Each time there would

Figure 26-14 A floating body

How much will be under water? The answer is 6.4 cm. (8 cm × 0.8 ÷ 1.0) How much of the block will be out of water?

Figure 26-15 Low-density sedimentary rock is buoyed up in denser crystalline rock, thus producing mountains.

be less of the block both above and below water. We can imagine the same thing happening to the Appalachian Mountains as a repeating cycle of uplift and peneplanation.

There is one great difference between our mental experiment and the Appalachians. There is almost no friction between the wooden block and the water. Therefore, buoyancy instantly causes the block to float in a perfectly balanced position. However, there is a great deal of friction in and between rocks when they are moved or bent. The buoyancy of the lighter rock "floating" in the denser rock must be greater than the friction between the rocks before uplift can take place. We still know very little about the forces needed to bend or move rocks. In one series of experiments it took 2,830 pounds of pressure per square inch to deform a block of limestone. (This is about 200 kilograms per square centimeter.) If we use that as a guide, and if the original thickness of the sediments in the Appalachians was 15,000 meters, we can make some rough estimates. Under these conditions, the original mountains must have been raised to about 3,000 meters (10,000 feet) above sea level.

Before such high mountains could be eroded (peneplained) to base level, buoyancy would have overcome friction and uplifted them. Calculations suggest that the present Appalachians are the result of four or five cycles of uplift and peneplanation. They also suggest that the region will go through several more cycles before buoyancy will be too small to cause deformation of the rocks and bring about uplift. Then the region will slowly be eroded to base level. That time is probably several hundred million years in the future.

Study Guide

1. Why do the heavy sedimentary rocks of the Appalachian Mountains not sink into the underlying crystalline rocks?
2. If uplift of rocks is to occur, which must be greater, buoyancy or the weight of the sediments? Explain your choice.
3. Why don't the Appalachians continually rise as they are eroded?
4. What can we tell about the rocks in an area that exhibits a negative Bouguer anomaly?
5. What allows a block of wood floating in water to adjust immediately if some of the wood is removed?

SUMMARY

The development of folded mountains, such as the Appalachians, appears to be related to slow sedimentation in a shallow trough in the ocean. This trough lies landward of an arc of volcanic islands.

Seaward of the island arc is a deep trench in the ocean bottom. The whole formation is called a geosyncline. As sediments accumulate in the trough, their weight depresses the crust beneath them. Oceanward of the island arc, volcanic sediments accumulate in the trench. Ultimately metamorphosed by heat and pressure, these are brought above sea level as new land.

Measurement of the force of gravity over ocean troughs and trenches indicates that it is less than expected. Lack of balance in the earth's crust may be the reason that the materials deposited in these depressions are forced upward and become folded mountains. The exposed rocks are later subject to erosion by streams. When the buoyancy of the sedimentary rocks embedded in denser crystalline rocks exceeds the strength of the crystalline rocks, they are again uplifted and the stream systems are rejuvenated. The cycle of uplift, peneplanation, and rejuvenation repeats itself until buoyancy is not great enough to raise the rock mass.

REVIEW AND DISCUSSION QUESTIONS

1. Why is a wind or water gap a good place to study the geologic history of an area?
2. If two streams were flowing over the same kind of rock, in which area, peneplained or rejuvenated, would they cut a channel more rapidly? Explain.
3. Discuss why the most rapid peneplanations and rejuvenations are to be expected in the early stages of mountain development.
4. Explain why the Appalachian region is considered to be an area of stable mountains.
5. Using Archimedes' principle of buoyancy (review this if you are not sure of it), answer the following question: If a block of wood (density = 0.6 gram per cubic centimeter) is floated in water, how much of the block will be above water?
6. Many of the original anticlinal and synclinal folds in the Sahara region of Africa are still complete. Explain why.
7. List some possible reasons for the extensive coal deposits found in western Pennsylvania and West Virginia.
8. What is the importance of the fact that areas of troughs and trenches in the ocean bottom exhibit gravity anomalies similar to those found in active mountain-building areas?
9. Most geologists think the forces that folded the eastern (seaward) side of the Appalachian island arc were greater than the forces that folded the western (landward) side. Explain why you agree or disagree with this idea.
10. Why are existing areas of active island-arc building poor places to plan the construction of new towns and cities?

CHAPTER 27

OTHER TYPES OF MOUNTAINS

Geologists have discovered that there are mountains formed differently than those we discussed in the last chapter. Some of these mountains, such as the Alps, are folded, but differently than the Appalachians. Other mountain ranges, like the Rockies, were formed by completely different processes. The recognition of most of these other kinds of mountains came about during the exploration of the western United States. Thus, much of what we know about mountains was originally discovered as a result of the fieldwork and observations of American earth scientists.

27-1 ALPINE-TYPE FOLDING

When you travel through and observe the Appalachian Mountains of Georgia and Tennessee, you find that they differ in some ways from the northern Appalachians. If you look back to the photograph at the beginning of Chapter 26 and Figure 26-9, you will see that the folding is simple and even. We say the folds are *symmetrical*. The mountains in Tennessee are not like this. The folds are uneven and lopsided. This is called *asymmetric folding*.

We believe this lopsided folding was caused by an excess of pressure from one side of the original pile of sediments. The Canadian Rockies contain many folds of this kind, but the most picturesque examples are found in the Alps of central Europe. In the Alps some of these folds are tipped so far over that they lie almost horizontal instead of standing up (see Figure 27-1). Such complex folding is called **alpine folding.**

The structure of alpine-folded mountains is very complicated. In cross section the uneroded folds must have looked something like the rocks shown in Figure 27-2. Each of these lying-down folds is called a **nappe**. Figure 27-2 shows that the rocks look as though they had been toppled over and

The Teton Range are young block mountains.

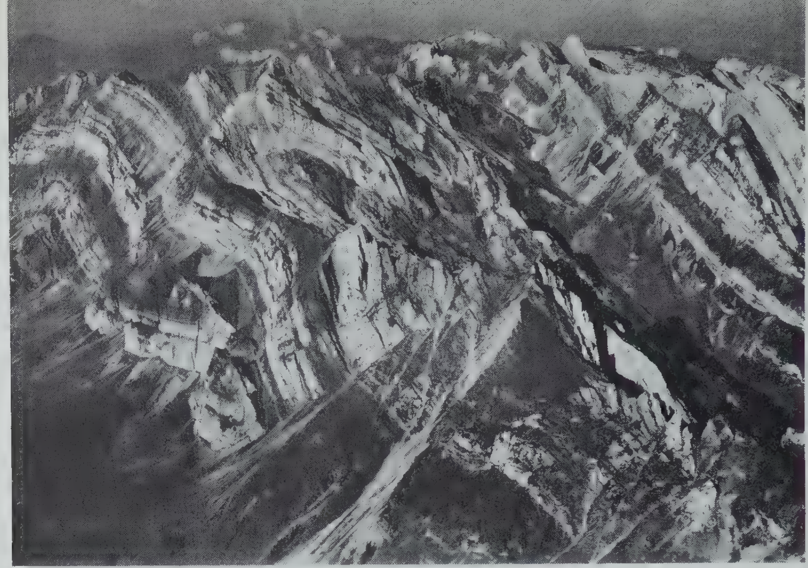


Figure 27-1 These faulted, overturned folds in the Swiss Alps are nappe formations.

pushed (thrust) along the underlying bedrock. The contact between the folded sedimentary rock and the crystalline bedrock is called the **thrust plane**.

Erosion has cut deep valleys into the nappe and formed "windows" through which the sequence of sedimentary rocks can be studied. As geologists studied the strata deeper and deeper in the nappes, they reached a point where the sequence of strata repeated itself in reverse. Figure 27-3 is a diagram of what can be seen through one of these windows. It was the discovery of these peculiar structures that gave geologists the clue to how they had been formed.

Somewhere on the side opposite to where the pressure was applied, the sedimentary rocks caught fast to the underlying crystalline rocks. The slowly flowing rocks started to pile up

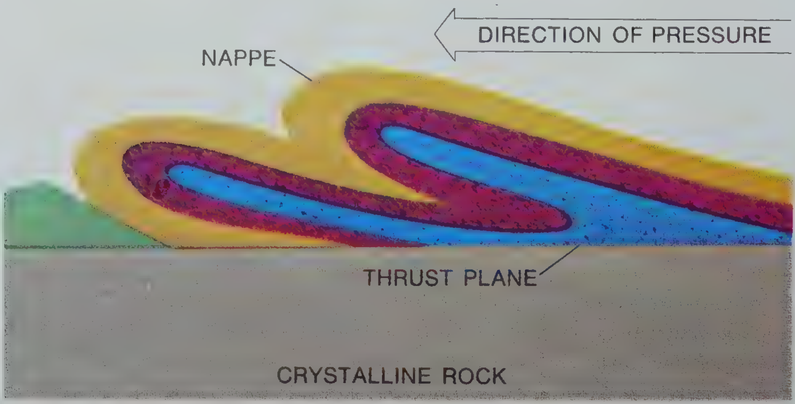


Figure 27-2 The sequence of layers of rock in a nappe. Pressure and surface movement can cause these folds to move miles from their point of origin.

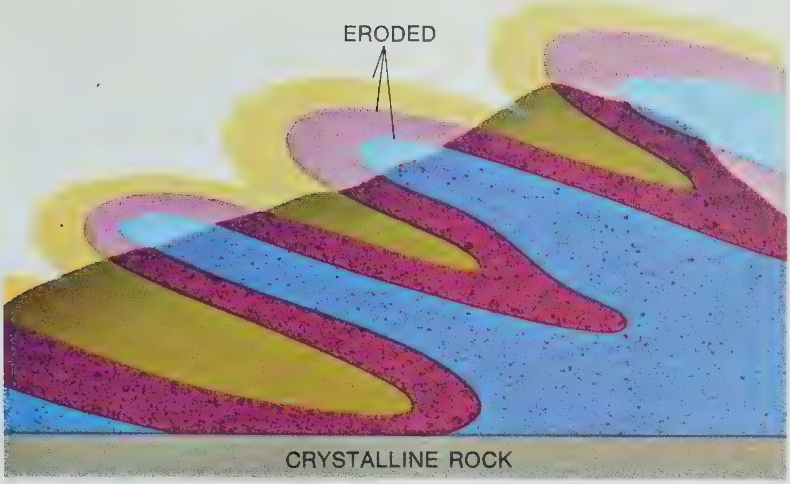


Figure 27-3 Eroded areas in the folds make it possible for geologists to recognize several repeating layers of sedimentary rock. This sketch also shows the layers of rock before they were eroded.

at the point where friction was stopping their motion. What finally happened is more easily seen in a diagram than described in words. Figure 27-4 is a diagram showing how the reversed sedimentary sequence shown in Figures 27-2 and 27-3 came about.

The modern Alps still show evidence of their original nappe folds. Millions of years of stream erosion have cut

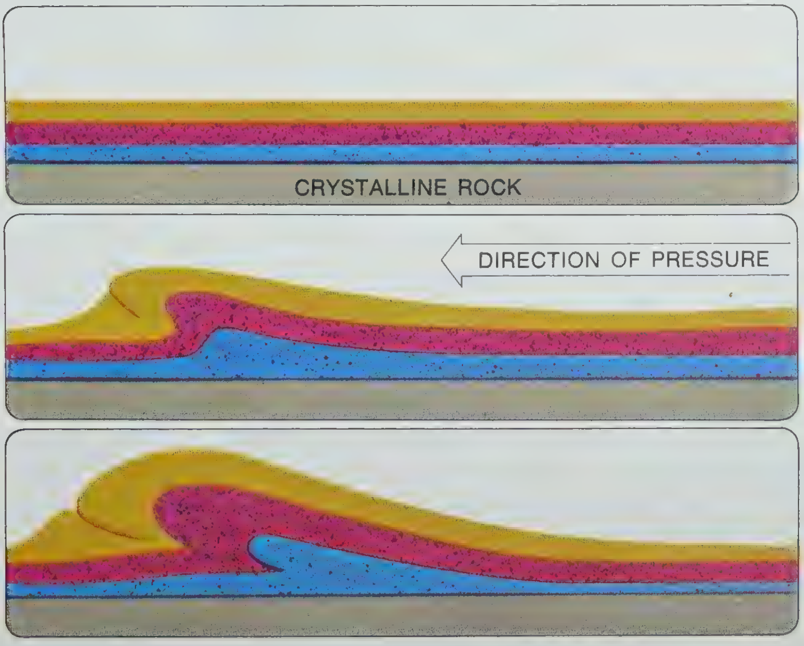


Figure 27-4 As pressure was applied to one side of the horizontal sequence of sediments, the material of the rocks became plastic and slowly flowed over the underlying crystalline rock.

deeply into the rocks, in some places exposing the underlying crystalline rocks. During the last one or two million years, mountain glaciers have further eroded the uplifted rocks. The combined actions of water and ice have carved the over-thrust folds into the picturesque mountains we see today.

Study Guide

1. Where are samples of asymmetrical folds found in the United States?
2. What is a nappe?
3. How does the sequence of sedimentary strata in a nappe indicate to geologists how the nappe was formed?
4. How is alpine folding different from the folding in the northeastern Appalachian Mountains?
5. Why are nappe folds not clearly seen in the Alps today?

27-2 FAULTING AND BLOCK MOUNTAINS

Figure 27-5 Pressure and uplifting of the land can cause small-scale faults in rocks undergoing metamorphosis.

Many of the mountain ranges in the western United States are fine examples of **block mountains**, a second kind of mountain. A range of block mountains is shown in the picture at the beginning of this chapter. These mountains form when a block of the earth's crust breaks loose from the adjoining crust and is raised or lowered. Some of these blocks are a hundred or more miles long and tens of miles wide.

A break in the earth's crust is called a **fracture**. Movement of the rock on either side of the fracture produces a **fault**. The movement may be of any distance and in almost any direction. Small-scale faults often occur in rock when it is being metamorphosed, as shown in Figure 27-5. The most famous large-scale fault in the United States is the San Andreas fault in California, described in Section 29-4.

Geologists know that a fault occurs when the earth's crust is under a bending or folding pressure. If this pressure overcomes the resistance of the rock to breaking, a fracture will occur. The breakage and movement along the fracture is the fault. Figure 27-6 shows the features of several kinds of faults.

We do not know why these huge pieces of crust break loose, nor are we sure of the sources of energy that cause them to move. We do know that the process of uplift takes place very slowly. It occurs slowly enough to permit major rivers to continue to flow across the uplifted regions. These rivers have been able to cut deep canyons through the uplifted blocks. Smaller streams usually cannot do this. They are

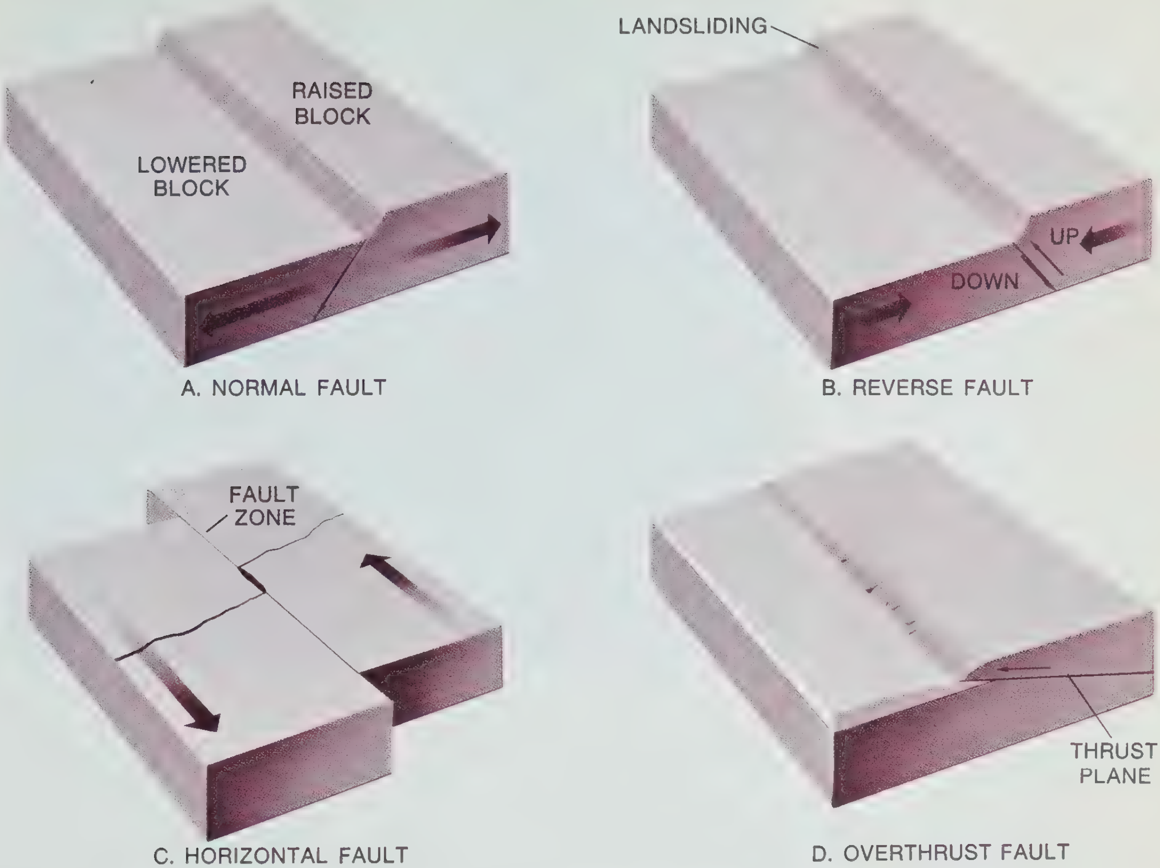


Figure 27-6 These four types of faults are the results of different types of pressure and rock layers. The way they appear at the surface gives them their names.

diverted from their old courses by the uplifted land and must establish new paths or disappear.

From what we know about the power of streams to cut channels into rock, it appears that the rate of uplift of a fault block mountain must range from about a third of a meter to more than two meters in a thousand years. The Arkansas River has cut the Royal Gorge to a depth of 330 meters (1,000 feet) through an uplifted block of granite. The Colorado River has cut the Grand Canyon to a depth of almost 2 kilometers (1.25 miles) in sedimentary rock. Both of these rivers have been eroding their present channels through uplifted blocks for about one million years.

Figure 27-7 The faulted, eroded blocks in the Wasatch Range in Utah appear as triangular facets.

There are several features of block mountains that are always present. First, the faults along the edges of the blocks tend to be more or less straight and parallel. Second, the blocks do not rise straight up. Usually, one side will rise faster and higher than the other. This places the highest point of the mountain range "off center" – nearer to one side than the other. Third, since the blocks rise slowly, stream erosion has time to modify the faces, or **facets**, of the uplifted block. It often shapes the sides of the blocks into triangular facets. Such formations are easily seen in the Wasatch Mountains in Utah, shown in Figure 27-7.

Normally, in a mountain not formed from a fault block, the ridges of the mountain extend onto the plain, as shown in Figure 27-8a. In fault block mountains, the ridges usually do not extend unbroken from the crest of the mountain to the plain. Instead, some distance back from the fault line, the ridge divides and forms two ridges, each extending downward toward the plain, as shown in Figure 27-8b. This produces the triangular facets shown in Figure 27-7. The facet faces the plain and represents the exposed side of the faulted block. If the facet has not been subjected to much erosion, it is easily recognized, but such a condition is rare. Usually the facet is eroded by small streams that flow over it. If the rock

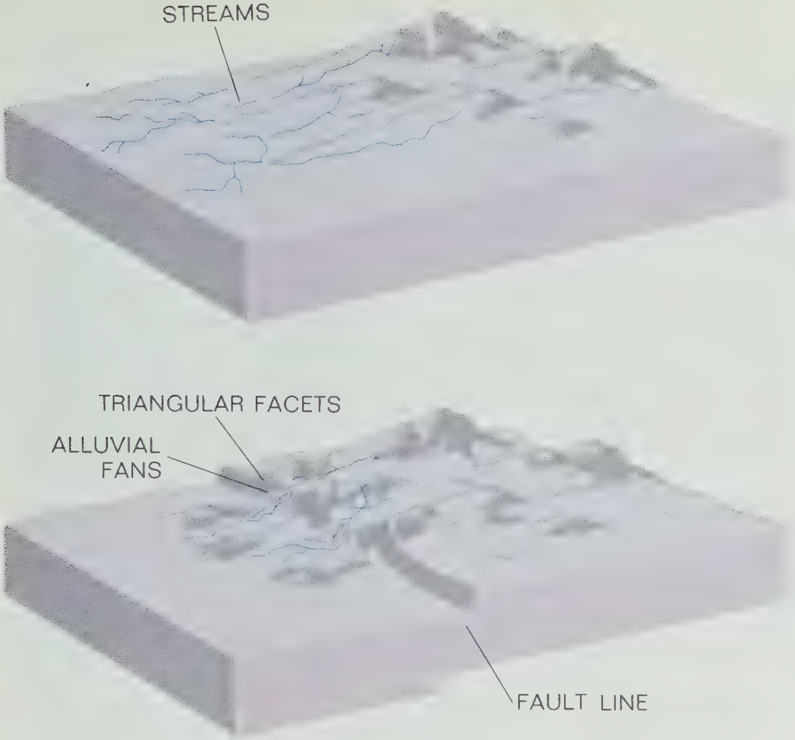


Figure 27-8 (*Upper*) When there is no block faulting, the mountain ridges extend in an uninterrupted line onto the surrounding plain. (*Lower*) When faulting occurs, the exposed cross section of each ridge is exposed as a triangular facet.

is soft enough, the stream may eventually destroy the facet completely.

A common form of faulting is the movement of a narrow section of rock relative to the surrounding rocks. If the movement of the narrow section is upward relative to the surrounding material, the uplifted section is called a **horst**. If the block sinks relative to its surroundings, it forms a **graben**. Figure 27-9 shows such a fault. A very large graben is sometimes called a **rift valley**. There are several such valleys in the eastern part of the African continent.

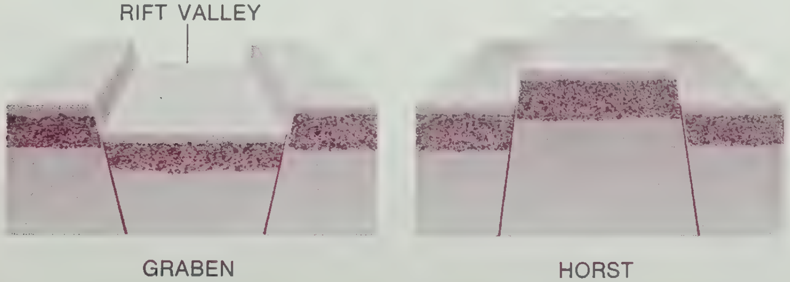


Figure 27-9 The uplifting or the downward thrust of rock forms horst or graben topography. Some riverbeds are grabens.

27-3 FAULTING AFFECTS WATER FLOW

Along the boundary faults of block mountains, the earth's crust is disturbed to a great depth. Water that seeps downward through the faulted rock meets heated rock and is in turn heated. If this water again rises to the surface, it flows out as a **hot spring**. Such springs are characteristic along the fault line of block mountains that are relatively young—only a few million years old.

Not all hot springs are associated with the faults of block mountains. Some, such as Hot Springs, Arkansas, are the result of an aquifer passing under a mountain of sedimentary rock, where compression causes the rock of the aquifer to become heated. Other hot springs are the direct result of volcanism.

Uplift of a block rejuvenates the streams in an area by increasing their gradients. This speeds up the rate of erosion of the stream bed. As long as erosion has kept pace with the uplift, the streams will continue to flow in their old channels. Very often, because the rising block is tilted, the smaller streams cannot do this and their direction of flow is reversed. This leaves a **notch** on the summit, representing the old stream channel.

Where the streams emerge from a block mountain region, their gradient changes rapidly. The steep mountain streams slow down and drop their loads. In Section 17-7 we described how alluvial fans are built at the mouths of canyons and valleys opening onto adjacent plains. The foot of a block mountain is a common place for the building of an alluvial fan. One is shown in Figure 17-11.

27-4 LIFE CYCLE OF A MOUNTAIN RANGE

geomorphic (jee uh MAWR fik); Greek: *ge*, earth; *morphe*, form.

The **geomorphic age** of a block mountain range depends on how much effect its streams have had on the rock. The geomorphic age does not depend on how many years it has been in existence. The effect of the streams depends on the kinds of rocks over which they flow, the amount of precipitation in the region, and the steepness of the mountains. Where there is little rainfall, mountains age slowly. Mountains of easily eroded rock age rapidly.

A *geologically young* fault block mountain range shows all the features we noted in Section 27-2. The mountains rise abruptly from the surrounding country along an easily recognized, almost straight fault line. The crests of the mountains

Figure 27-10 The White Mountains of New Hampshire are geologically mature.

are not yet cut into individual peaks but tend to be notched at places where a stream's flow was reversed during the uplift. Triangular facets are clear-cut when viewed from the lowlands. At the mouth of most valleys is a well-defined alluvial fan. The Teton Range, pictured at the opening of this chapter, is a young mountain range.

As the mountains age, the crest line is eroded into clusters of rugged mountain peaks. The range is then *geologically mature*. Figure 27-10 shows a mature mountain range. The faces of the triangular facets become eroded and are difficult to recognize. The alluvial fans grow so large that they join one another, forming a sloping **piedmont belt** of alluvium. Gullies, or even small canyons, are cut into this huge deposit of sediments.

Ultimately, erosion reduces the once majestic peaks to a series of gentle hills. The streams flow slowly and have lost their power to cut into the rock. The eroded material carried away from the mountains is now spread over a wide region surrounding the hills. The block mountains have reached

geomorphic old age. Often uplift rejuvenates the streams before old age is reached. This sequence of events is very similar for folded mountains, although the details are different. It also applies to a third kind of mountain, to be discussed in the next section.

Study Guide

1. What is a fault?
2. How was the Grand Canyon formed?
3. Why are hot springs common along the edges of young fault block mountains?
4. How are triangular facets formed?
5. What is meant by the geomorphic age of a mountain?
6. Describe the differences between a young and an old mountain range.

27-5 DOME MOUNTAINS

In the 1870's, G. K. Gilbert, a young geologist recently hired by the United States Geological Survey, was assigned to study a region in the western United States. One of the areas he explored was the Henry Mountains in Utah, shown in Figure 27-11. He soon realized that these mountains showed no signs of having been folded or of having been carved from an uplifted fault block.

Figure 27-11 A view of the Henry Mountains in Utah

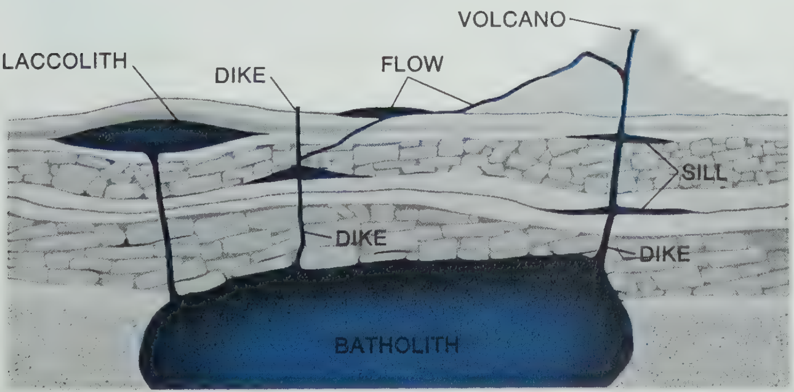
Gilbert is credited with discovering a third type of mountain. Such mountains can be compared with a blister on your hand. A blister is caused by the accumulation of blood serum between the layers of your skin. The mountains Gilbert discovered formed when liquid rock, or **magma**, accumulated either between or beneath sedimentary strata. In both cases, magma causes the layered material above it to bulge upward. Such mountains are called **dome mountains**.

Dome mountains are formed as a result of a kind of volcanism, which is discussed in detail in Section 28-5. Domes vary greatly in size and shape. Some are quite small, about a mile in diameter, and almost circular. Others are elliptical and many miles long. The Henry Mountains are among the larger type—about 50 miles long.

All dome mountains have one feature in common. A mass of magma intruded into or beneath sedimentary rock, causing the overlying material to arch upward. Where the intrusion took place *between* strata, the solidified magma is called a **laccolith**. Where the magma intruded *under* a column of sedimentary rocks and covered a large area, it is called a **batholith**. Figure 27-12 shows how laccoliths and batholiths form.

The western United States has many small and large dome mountains. The Adirondack Mountains in New York State are carved from a Precambrian batholith that has been uplifted and exposed at the surface. The Black Hills in South Dakota show many of the features common to all domes, so we shall now study them in detail.

Figure 27-12 The formation of laccoliths and batholiths. Both these intrusions of magma appear as rounded domes. Note the formation of dikes and sills by magma that has intruded upward and horizontally.



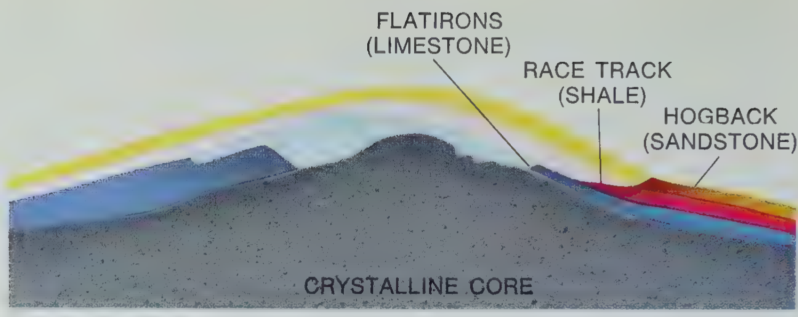
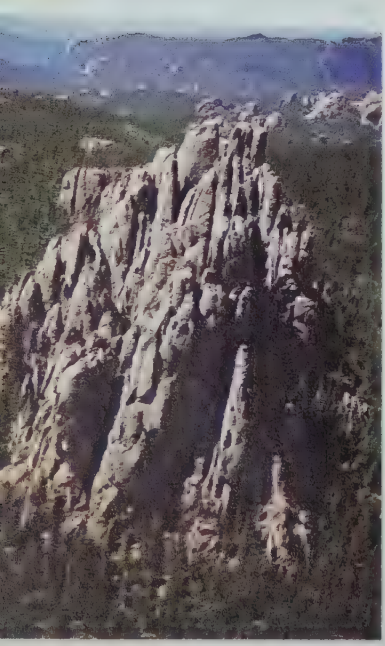


Figure 27-13 The geology of the Black Hills in South Dakota is shown in cross section. The various strata of rocks are exposed as the result of erosion of the once overlying sedimentary rock.

27-6 THE BLACK HILLS

The dome from which the Black Hills have been eroded straddles the border of Wyoming and South Dakota. Most of the dome lies in South Dakota. It is an almost perfect ellipse, about 100 miles long from north to south and about half as wide from east to west.

Figure 27-14 A view of the Black Hills in South Dakota



Erosion has removed most of the sedimentary rock that once covered its eastern half. The western half is still capped by layers of resistant limestone. In the central area, Precambrian crystalline rock has been exposed. Laccoliths may have intruded during the Cretaceous Period and raised this crystalline rock and the sedimentary rock above it into the Black Hills dome. Figure 27-13 shows the various rock types of the Black Hills, and Figure 27-14 is a photograph of part of the actual mountains.

Geologists have wondered why the sedimentary cover on the eastern half eroded away, while the sediments on the western side were not disturbed so much. Perhaps the bulging of the rocks of the eastern portion of the dome caused them to crack and break more than the rocks on the western side of the dome.

Surrounding the Black Hills on the east is a ridge of upturned sandstone called the Dakota Formation. The broken and eroded face of the ridge that faces the dome is steep and may be several hundred feet high. Such a ridge is called a **hogback**. An encircling hogback ridge is characteristic of eroded dome mountains.

Between the hogback and the dome is a broad valley, eroded from a soft, red-colored shale deposited before the Dakota sandstone. The soil produced from the shale gives the name

Figure 27-15 Flatirons in the mountains near Boulder, Colorado

Red Valley to this structure. The Indians called it the *Racetrack*. Where such valleys occur around other eroded domes, they are also called racetracks. You can see a hogback and a racetrack in Figure 27-13.

Beneath the red shale is a layer of hard limestone deposited directly on the Precambrian crystalline rock. Like the Dakota sandstone, the limestone has resisted erosion. It lies "plastered" against the older rock of the central core and has been cut by streams. Between the stream valleys, the more or less triangular slabs of limestone look like old-fashioned flatirons standing on their heels. Such a triangular slab of sedimentary rock resting against crystalline rock is called a **flatiron** (see Figure 27-15).

Streams have also eroded valleys into the crystalline core, leaving behind huge peaks of granite. One of these, Mount Rushmore, is famous for the gigantic sculptures of Presidents carved on its face. Only one or two of these granite peaks reach as high as the uneroded limestone covering the western half of the dome.

Streams have also cut valleys into the tough limestone. The most spectacular of these is Spearfish Canyon, 1,000 feet deep, at the northern end of the dome. Along the western perimeter of the Black Hills, called the limestone plateau, are several low hogback ridges cut into the limestone. The limestone plateau slopes very gently to the surrounding

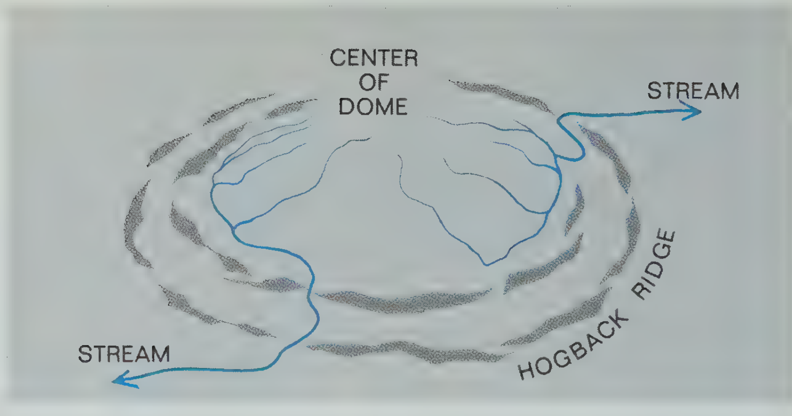


Figure 27-16 The drainage pattern in an eroded dome mountain

plains and is surprisingly different from the eastern perimeter of the dome. By comparing the two sides, geologists have learned much about the way rugged mountains can be produced from a smoothly rounded dome.

The streams associated with dome mountains produce characteristic patterns of flow. Figure 27-16 shows these patterns. The courses of the streams radiate in all directions from the central, highest point on the dome. On a circular dome, this produces a drainage pattern that resembles the spokes of a wheel. These patterns are called **radial drainage patterns**. The radiating streams usually flow for some distance in the racetracks before breaking through the hogback ridges. The streams flowing in the racetracks around the dome are said to have an **annular pattern** of flow.

Not all domes have been eroded enough to expose the crystalline core. This sometimes makes it difficult for a geologist to determine the kind of mountain he is studying. If a dome is elongated rather than circular, it may look like a single, small fold.

Study Guide

1. How is a dome mountain like a blister on your skin?
2. How are hogbacks formed?
3. Explain why the Black Hills are composed of granite but are almost completely surrounded by sedimentary rock.
4. Why is a radial drainage pattern characteristic of the streams on a dome mountain?
5. What is a flatiron? How does it form?

27-7 OTHER KINDS OF DOMES

On the coastal plain of Mexico and Texas are a great many low, domed structures. At first these were thought to be monadnocks, the special hills described in Section 26-5. Now we know they were built by chemical action in certain kinds of sedimentary rocks.

Most of the domes on the coastal plains of Louisiana, Texas, and eastern Mexico are made of salt. A few sulfur domes have been found. Many of the salt domes are associated with deposits of petroleum and natural gas.

Sometimes a thick layer of salt or a material called gypsum is deposited at the bottom of a shallow lagoon. This probably happens when a lagoon forms in a region where there is little precipitation and a high rate of evaporation. Conditions in the Southwest during the Permian Period were suitable for this type of deposition. As the water evaporates, the salt concentration of the lagoon increases to the point where the water becomes saturated. Any further evaporation causes the dissolved salts to come out of solution and to be deposited on the bottom. Layers of deposited salts may be part of a column of sedimentary rocks.

The presence of water and bacterial action appears to affect a deposit of gypsum, a calcium salt. Bacteria chemically change the gypsum, which is calcium sulfate, to limestone, sulfur, and water. The limestone, sulfur, and water that are produced take up more space than the original deposit. This causes the sedimentary layers above the gypsum to bulge upward, forming a dome. Such domes are rarely more than a few tens of feet high. An unusually large one may be 100 feet high and a mile and a half in diameter. Today millions of tons of sulfur are mined from such domes on the western perimeter of the Gulf of Mexico.

Ordinary salt deposits produce another kind of dome. Rock salt (the mineral halite), which is the raw material from which table salt is refined, has a peculiar property. Under pressure, rock salt flows easily but only if the pressure is uneven. Part of the flow seems to be plastic, like that of glacial ice. Most of the flow is due to the actual movement of molecules or groups of molecules "rolling" over one another.

As long as a layer of halite is under uniform pressure, it tends to stay in place. If part of a stratum is under a heavy mass of sediments, and the other part is not, the halite will flow out from under the heavier mass. As the amount of salt in the region of lower pressure increases, it lifts the material above it into a low dome.

In the arid western part of Colorado and in eastern Utah are several interesting valleys that were originally large salt domes. One of them, Paradox Valley, is about 2 miles wide and between 10 and 12 miles long. When streams began to erode the sedimentary covering of the original salt dome, they exposed the underlying salt. The salt began to dissolve in the water and was washed away. Eventually, so much of the salt was dissolved and washed away that the sedimentary cover collapsed into the empty area that had once been filled with salt. The dome became a valley. Some of the salt domes in the Gulf coastal plain have also collapsed, forming such valleys.

Study Guide

1. How does a sulfur dome form?
2. Explain the flowing of rock salt.
3. Why is a shallow sea a good place for a salt dome to form?
4. Why are many salt and sulfur domes found in the southwestern United States?

SUMMARY

Mountains and mountain ranges may be formed by faulting of the earth's surface and by volcanism as well as by folding. Each kind of mountain has certain characteristics that enable a geologist to tell how it was formed. Block mountains occur when a block of rock breaks away from the surrounding material and moves. The movement is usually upward or downward, but it may be in a horizontal direction.

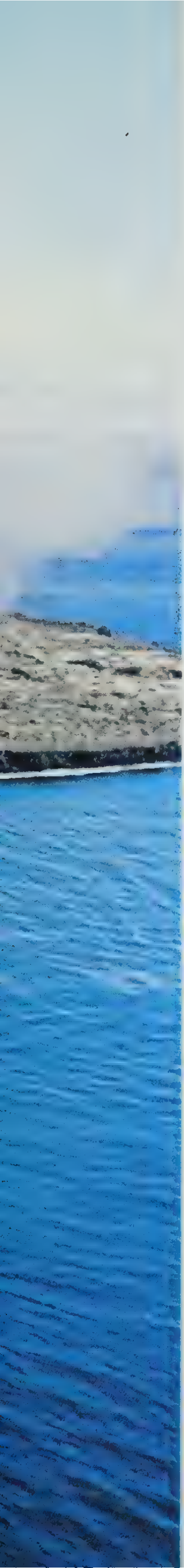
Mountains go through a "life cycle." The stages of the cycle are based on how much the original mountains have been eroded by streams. The stage of the cycle is only indirectly related to the age in years. Young mountains are high, rugged, and cut by young, fast-moving streams. Mature mountains have been eroded into individual mountain peaks. Alluvial fans, canyons, and streams with medium gradients are found in mature mountains.

Dome mountains are formed when magma is intruded beneath or between sedimentary strata. This forces the overlying material to bulge upward, forming a new mountain or mountain range. Usually, the sedimentary rocks that form the dome are eroded away, exposing the central igneous rocks of the dome.

REVIEW AND DISCUSSION QUESTIONS

1. Describe the changes that occur in an old mountain range when it is rejuvenated by uplift.

2. What is the lowest level to which streams can erode a dome? Why?
3. Why should the plains at the foot of a young fault block mountain be a good place for farming?
4. Why are the exposed cores of most dome mountains composed of granite rather than basalt?
5. How may the structure of the mid-ocean rift, described in Section 25-8, be related to the structure of a fault block?
6. Describe the differences that must have existed between the forces that produced the northeastern Appalachians and those that produced the Alps.
7. Explain why the present structure of a mountain range may not be a clue to how it was formed.
8. What evidence would a geologist look for in order to determine how a mountain range was formed?
9. The portion of the Grand Canyon usually seen by tourists is where the Colorado River has cut a gorge more than a mile deep and about 4 miles wide. What kinds of conditions probably existed there before the river began to erode the gorge?
10. Describe the stages a dome might pass through from the time it is originally formed until all that is left in its place is a monadnock.
11. Why are young domes more difficult to study than older domes?



CHAPTER 28

VOLCANISM

In the last chapter, you learned that hot springs are often associated with the fault zones that border block mountains. In an earlier chapter, you learned that volcanoes are associated with the faults along an ocean trench. In fact, so many volcanoes are associated with the island-arc—ocean-trench systems which ring the Pacific that they are called a "ring of fire" (see Figure 28-1).

Hot springs and volcanoes suggest that somewhere inside the earth there is a source of great heat. It may be worthwhile to seek this buried source. Before we try to discover the reasons for heat deep in the earth, let us look at the evidence where it can be studied easily—at the surface.

28-1 VOLCANOES

The most spectacular evidence that we have of activity occurring beneath the surface of the earth is the volcano. In its perfect form, a volcano is a cone-shaped mountain or hill. It is built of the material thrown out of an opening at the summit. The great variety of particles forcefully thrown out by an erupting volcano are called **ejecta**. This material ranges from blocks of lava that may be the size of a small house to fine, dustlike ash (see Figure 28-2).

Most ejecta are small, irregularly shaped masses called **cinders** or **scoria**. A volcano composed entirely, or almost entirely, of ejecta is called a **cinder cone**. One composed of alternating layers of ejecta and lava is called a **composite cone**. The volcanoes that make up the Hawaiian Islands are composed completely of solidified lava and are known as **shield volcanoes**. Examples of all three types are shown in Figure 28-3. The depression or opening found at the top of all three types is called the **crater**.

28-2 VOLCANOES IN ACTION

In 1943 a crack developed in a cornfield near the town of Parícutin, Mexico. At first, steam and hot gases issued from the

Volcanic islands off the coast of Iceland. Surtsey is in the background, and the island in the foreground has now disappeared.

Figure 28-1 The major volcanic areas in the Pacific almost form a circle. This region is known as the "ring of fire."

crack, called a **fissure**. Within a day, the fissure had enlarged to become a large hole in the ground, a **vent**. Red-hot bits of rock were thrown from the vent while it continued to enlarge. As the activity increased, more and more glowing, hot pieces of basalt were ejected. Around the vent, a cinder cone of scoria and basalt blocks was built up higher and higher.

Figure 28-2 This volcanic bomb is an example of ejecta from an erupting volcano (see Section 28-6).

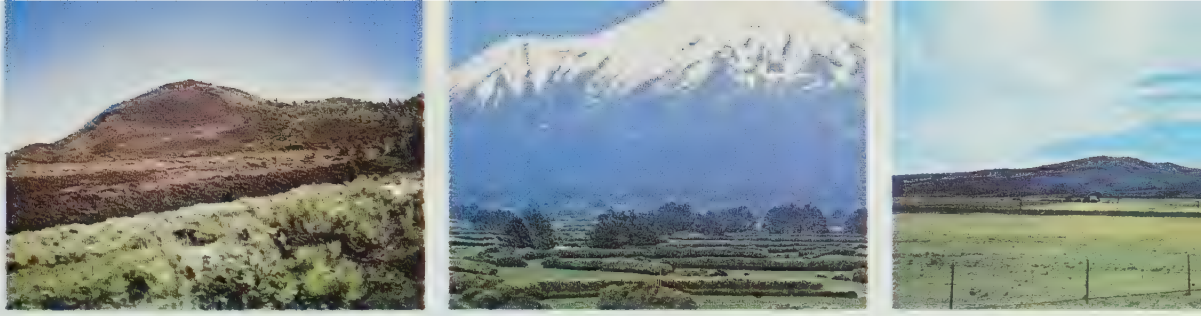


Figure 28-3 The three types of volcanoes: *(from left to right)* cinder cone, composite cone, and shield volcano

The cone was almost 1,000 feet high before Parícutin was 1 year old (see Figure 28-4).

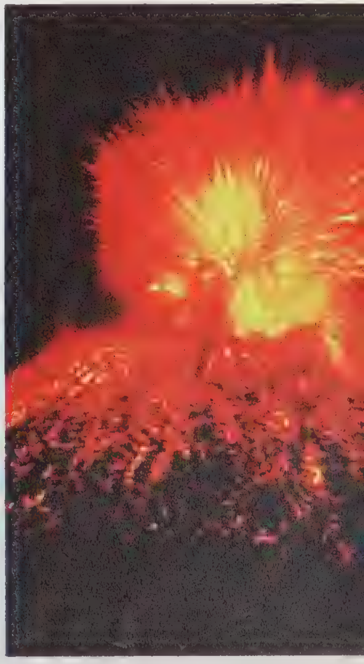
Faults, from which oozed thick, plastic basaltic lava, developed in the region surrounding Parícutin's vent. As the intensely heated rock pushed away from the faults, the surrounding scrub forest burst into flames. Slowly the half-flowing, half-tumbling mass of lava moved over the town, burying all except the top of the church steeple.

On the flanks of the growing cinder cone, new vents opened up. Their eruption built small **parasite cones**. Throughout the period of several years when Parícutin was growing, the earth in the vicinity trembled from hundreds of mild earthquakes. Slowly the activity ceased, except at the main crater and in several of the parasite cones. Ultimately, these also quieted down. Now Parícutin is dormant. Whether it will erupt again, no one knows.

Volcanoes are rarely continuously active. Usually they remain dormant for long periods of time and then erupt. These are signs of the earth's unstable crust. Until the crust in the vicinity of a volcano becomes stable, there may be eruption at any time. Stromboli, a volcano on an island off the coast of Italy, is called the Lighthouse of the Mediterranean because it is continuously in eruption. This is a most unusual situation and has been occurring for more than 2,000 years. Because such a volcano is constantly "letting off steam," the forces within it never accumulate to the point of causing a serious, explosive eruption.

In 1965, fishermen working a few miles off the coast of Iceland saw the birth of a new island, a volcanic cone that rose from the Mid-Atlantic Ridge (see Figure 25-12). As this is being written, Surtsey, the new volcano, is still growing. Its growth is being watched and recorded by an international group of volcanologists.

Figure 28-4 Parícutin, in Mexico, is one of the few volcanoes that scientists have been able to study from the moment of its birth.



Japanese scientists have watched and recorded the same kind of events taking place near the Mariana-Japan trench in the Pacific Ocean. The new volcano there is called Myojin-sho. Among the Aleutian Islands near Alaska, a cluster of volcanoes called Bogoslof Island has been changing rapidly. In the past century, many charts have been made of the area. Each time survey ships have visited Bogoslof, the island has had a different shape.

Study Guide

1. What evidence is there that some faults extend downward into hot rocks?
2. What type of volcano is found in Hawaii?
3. How rapidly did the volcanic cone of Parícutin develop?
4. What kinds of acitivity were associated with the volcano Parícutin?
5. Give the name of a volcanic island that recently arose from the Mid-Atlantic Ridge.

28-3 VOLCANOES IN THE UNITED STATES

The greatest volcanic eruption of historic time occurred on June 6 and 7, 1912, in Alaska, when Novarupta exploded three times within 24 hours. Novarupta is a parasite volcano on Katmai, an ancient volcano that had been dormant for a long time. Seven cubic miles of ejecta were blown into the atmosphere. Withdrawal of so much material from the magma pool of Katmai caused the older volcano to collapse and form a **caldera**. At the same time, the Valley of Ten Thousand Smokes, seen in Figure 28-5, came into being nearby. Although the ashfall and accompanying earthquakes were severe, no human lives were lost during this eruption. The region is now dormant.

caldera (kal DEHR uh). An immense depression formed when a volcanic cone has caved in.

Figure 28-5 The Valley of Ten Thousand Smokes is in Katmai National Monument. Katmai is the most spectacular volcano in this region.

The states of Hawaii and Alaska contain many active volcanoes. Each of the Hawaiian Islands is the peak of a gigantic shield volcano that has its base some 14,000 feet below sea level. Some of the volcanoes, such as Mauna Loa, rise more than 26,000 feet from the bottom of the ocean. At the summit of Kilauea, a part of Mauna Loa, is the Hawaiian Volcano Laboratory, operated by the United States Geological Survey.

One of the many eruptions of the volcano Kilauea, on the island of Hawaii, occurred in 1959. For over a year, J. Eaton and K. J. Murata had been observing and measuring the earthquake waves being produced under the volcano. They had also set up tiltmeters around the flanks of Kilauea to measure any changes in the shape of the mountain. They discovered that the intensity of the earthquake waves and the bulging of the sides of the volcano were rapidly increasing. From such data, they were able to predict that an eruption would soon take place. It did!

A tiltmeter is a very sensitive instrument that measures the tilt or bulging of the earth.

When it finally happened, the huge caldera of Kilauea became filled with a lake of molten lava 400 feet deep. As the lava poured out of the interior of the volcano, the sides began to contract and resume their normal shape. The eruption lasted until April 1960. For the first time, man had predicted, observed, and measured a volcanic eruption. Figure 28-6 shows one of the 500-foot-high lava fountains erupting from the lava lake in Kilauea.

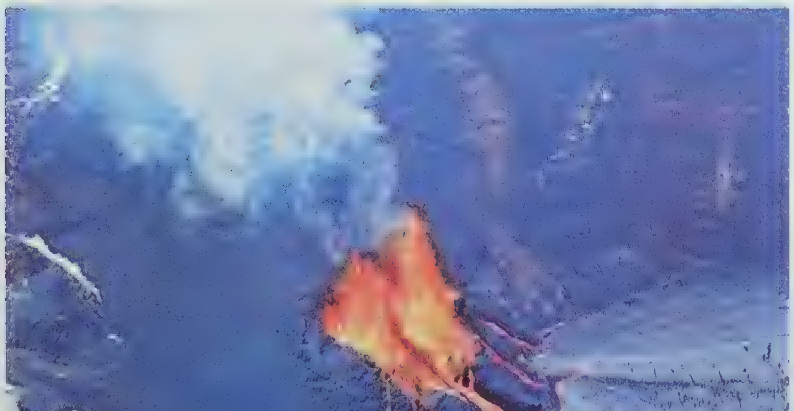


Figure 28-6 A lava fountain erupting from the floor of Kilauea

Almost all the states show some signs of past volcanic activity. Only a few states in the Mississippi Valley appear to be without such signs. These are the states that have such a deep covering of sedimentary rock over the crystalline basement rock that any evidence of early volcanism is hidden.

Along the eastern seaboard are the remains of ancient volcanoes associated with the origin and development of the Appalachian Mountain system. All western states, except possibly Oklahoma and Kansas, have either volcanoes or the evidence that they once existed. Three national parks—Lassen Volcanic, Crater Lake, and Mount Rainier—and two national monuments—Capulin Mountain in New Mexico and Craters of the Moon in Idaho—were set aside to exhibit volcanism.

A little more than 4,000 years ago, there was a towering mountain, now called Mount Mazama, where Crater Lake National Park now stands. It was an old volcano, crowned with beautiful mountain glaciers, and had long been quiet. Suddenly Mount Mazama became active and poured scoria and ashes over thousands of square miles. The ejecta buried some nearby Indian villages. Archaeologists have retrieved sandals and other artifacts from the buried villages, and these have been dated by the carbon-14 method.

As the eruption came to a close, the removal of material from under the volcano so weakened its sides that they collapsed, forming a caldera. This series of events is shown in Figure 28-7. The caldera filled with water and became a deep lake. In it is found the remains of a cinder cone, called Wizard Island (see Figure 28-8). In the rim of the caldera can be seen the U-shaped troughs that once held mountain

Figure 28-7 The eruption of ancient Mount Mazama was so severe that the mountain literally blew its top. The absence of magma under the floor of the crater caused it to collapse, forming a caldera.

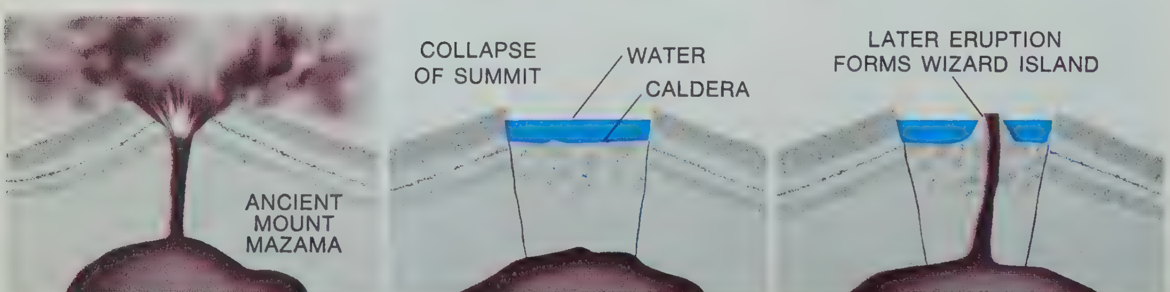


Figure 28-8 Wizard Island in Crater Lake is the remains of a cinder cone that formed after the floor of Mount Mazama collapsed. The caldera filled up with water and became Crater Lake.

glaciers descending from the now vanished summit of Mount Mazama.

The most recent volcanic eruption in the continental United States occurred at Mount Lassen in California. In 1917 this dormant volcano erupted and poured lava down its eastern flanks, engulfing and burning the forests that had grown there. During the nineteenth century there were several active cinder cones in Idaho and California. Mount Hood in Oregon may have erupted at that time also. In recent years, the summit of Mount Rainier in Washington has shown signs that it is not dead. While testing a new kind of film and space camera, NASA scientists discovered several previously unrecognized, dormant volcanoes in the western United States.

Geologists do not restrict the term *volcanism* to activity that produces volcanoes. Along the Columbia River in Washington and Oregon and the Snake River in Idaho are extensive plateaus composed of hardened basaltic lava. The lava oozed out of faults and flowed over the adjacent land, filling in the hollows and overrunning the hills. Figure 28-9 shows some of the more than 300,000 square miles covered by these lava sheets. These masses of lava are called the Columbia and Snake plateaus.

Study Guide

1. Which of the 50 states is entirely volcanic?
2. What section of the United States appears to have been free of volcanic activity?
3. What is a caldera?
4. Describe how Wizard Island was formed.
5. What condition must prevail in the crust of the earth if a volcano is to become completely dead?
6. How do lava plateaus develop in a volcanic region?

Figure 28-9 The lava sheets along the Columbia River gorge

28-4 LIQUID ROCK

The lava that escapes through volcanoes is magma that has reached the surface of the earth. Any description of lava must first explain the formation of magma, or liquid rock. It is obvious from much of the evidence geologists have collected that the earth does not consist of a solid crust surrounding a completely liquid interior. Some of the evidence is based on earthquake waves and on gravity and density measurements. For other evidence, see the note in the margin.

Try this simple experiment at home. Spin a hard-boiled egg and an uncooked egg. Which spins longer and more easily? Why? The answer is related to how the internal structure of the earth affects its rotation.

If the earth is not composed of a completely liquid interior, we must account for the formation of magma wherever volcanoes occur. In other words, magma seems to form locally or at certain spots within the earth.

In order for such local magma pools to form, heat must be present in small "pockets." A source of such heat within the earth is the decay of some of the radioactive isotopes of elements. As a radioactive isotope loses particles, it also loses energy. The energy may be absorbed by surrounding matter, which becomes hot. The most common radioactive isotopes in the earth's crust are potassium-40, thorium, and uranium.

The rocks that contain a source of radiation may be of any type, but evidence shows that for some reason granitic rocks are the most radioactive. Since rocks are poor conductors of heat, it is possible that they may absorb and retain enough energy to melt.

Radiation cannot be the only source of magma-forming heat. The most common types of extrusive magmas are basal-

tic rocks. However, such rocks contain very little radioactive material. The melting of basalt, according to many geologists, is not caused by radiation. Their evidence is based on three discoveries made about the earth.

First, the temperature of rocks increases the deeper we go into the crust of the earth. The rate at which the temperature rises has been measured in deep mines and oil wells. Measurements of this **thermal gradient** within the crust show it to average 50F° per mile. At a depth of about 19 miles, it has been estimated that the temperature ranges from 300° to 680°C (about 550° to 1250°F). What causes this heat? Some of it comes from radioactivity. Other causes are heat escaping from deep in the earth, heat caused by the pressure of overlying rocks, and frictional heat produced during faulting.

Rocks are poor conductors of heat. Therefore, heat may accumulate faster in them than it can escape. This is especially true when faulting suddenly adds more heat to rocks that are already hot. Under such conditions the temperature of the rock may rise above its melting point. Whether the rock does melt or does not depends upon a second discovery.

Physicists have known for a long time that the melting point of a substance is affected by pressure. Pressure raises the melting point of rocks. Figure 28-10 shows this relationship. Thus, at depths of tens of miles below the surface, a rock may be solid although its temperature is well above its laboratory melting point.

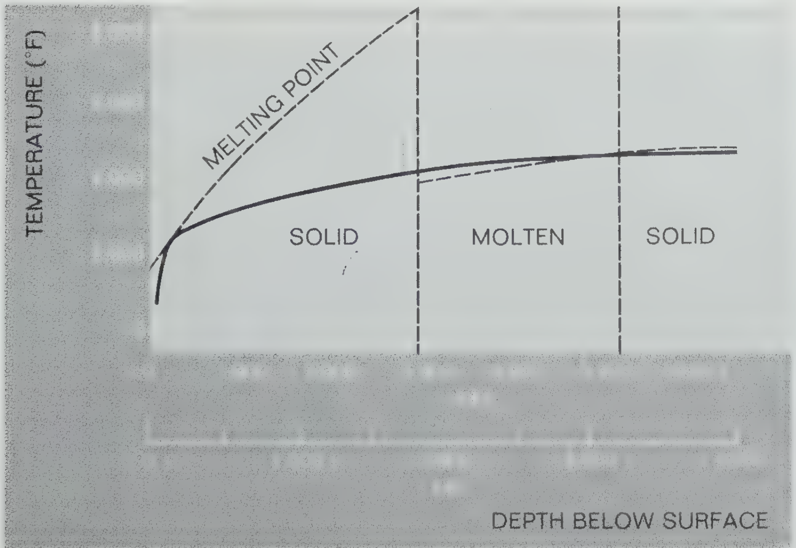


Figure 28-10 Pressure increases with depth in the crust of the earth, resulting in an increase in temperature. The melting point of the crust is related to depth.

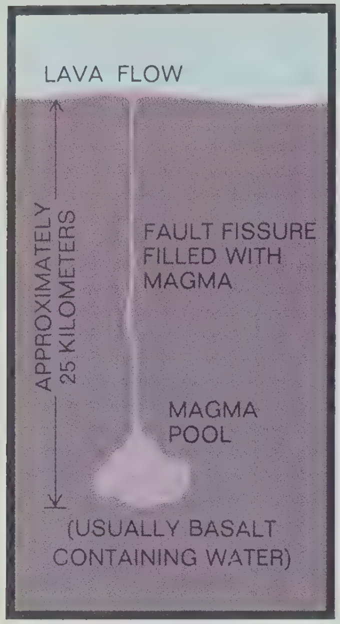


Figure 28-11 Fault–magma pool relationship

A third discovery helps us understand why pockets of rock deep in the earth's crust may melt. Faults extend downward into the crust to varying depths. Some of them probably reach 30 to 40 miles below the surface of the earth. If a fault reaches a zone where hot rocks are kept solid only by pressure, what would happen? The fault would relieve the pressure and the rocks would melt. See what we think happens, as shown in Figure 28-11.

The next logical question to ask would be: How does magma reach the surface to become the lava in a volcanic eruption? You know that as a substance heats or melts, it expands. The magma pool will expand at a rapid rate as the pressure on it is relieved. Depending on the size of the magma pool, the amount of pressure it was under, and other factors, the expansion of the magma pool will have one of two effects. The expansion may bulge the earth above the expanding magma pool, forming a batholith. Or it may force magma through a fault to the earth's surface.

28-5 SILLS AND DIKES

Not all evidence of volcanism is visible on the surface of the earth. Shiprock in New Mexico (see Figure 28-12) is a plug of basalt that once filled the throat of a cinder cone, like Wizard

Figure 28-12 Shiprock is the remains of a basaltic plug that once filled the throat of a cinder volcano. The Navaho Indians of New Mexico consider this formation a sacred object.

Figure 28-13 The Devils Postpile National Monument is an example of columnar jointing of basalt.

Island. Erosion has removed the scoria that once hid the solid basalt. It has also exposed the long vertical walls of rock that you see in the picture. These walls of intruded material are called **dikes**. At the time of volcanic activity, magma flowed into great cracks that radiated from the vent of the volcano. This solidified into rock harder than the surrounding kind. Another interesting example of dikes radiating from an old volcano may be seen at the Spanish Peaks located in Colorado.

Sometimes magma being forced upward through a fissure finds a weak place between strata of sedimentary rocks. There the magma may flow horizontally between the strata, forming an intrusion known as a **sill**. One of the best-known sills is the Palisades in New Jersey, along the banks of the Hudson River. They were formed during the Triassic Period, and are hundreds of feet thick. They look more like a vertical dike than a horizontal sill. The vertical appearance of the rock is caused by **columnar jointing**, and occurs when basaltic magma cools slowly. A fine example of columnar jointing is seen in Figure 28-13.

Study Guide

1. What is a dike?
2. How were the Palisades of the Hudson River formed?
3. What is a thermal gradient? How does it affect the earth's interior?
4. How does the decay of radioactive isotopes deep in the earth heat the surrounding rocks?
5. What could release the pressure on deeply buried rocks?
6. How may areas of the earth's surface be bulged upward by magma?

28-6 VOLCANIC ERUPTIONS

Thick, molten lava is the material most of us imagine pouring out of a volcano during an eruption. Actually, not all eruptions are accompanied by lava flows. Four different kinds of material are produced by volcanoes. All of them are the product of the intense heat found within the earth. Any combination of these materials may accompany an erupting volcano.

Lava is the molten rock that issues from volcanoes. It is classified into different types, all based on the kinds produced by the Hawaiian volcanoes. Although the two major kinds of lava have many variations, they are basically **aa**, or "blocky" lava, and **pahoehoe**, or "ropy" lava. Examples of both types are shown in Figure 28-14.

Aa is crumbly, uneven lava formed when the surface of a molten lava flow cools rapidly. The solid crust is carried

Figure 28-14 These examples of pahoehoe *(top)* and aa lava were found in the basaltic flow in Craters of the Moon National Monument.

Figure 28-15 Pillow lava is one of the rarest forms of lava. It forms where a lava flow meets water.

along by the still molten material underneath and breaks up into jagged chunks. Pahoehoe is lava that has cooled more or less evenly. It forms a smooth, billowy surface.

Occasionally, lava flows into water while still molten. There it cools almost instantly, and a structure resembling a group of pillows is formed. This is pillow lava (see Figure 28-15).

Under other conditions, the surface of a lava flow will harden enough so that it will stop flowing. The molten lava underneath may flow out from under the solid surface. This leaves a hollow arch of hardened lava called a **lava tunnel**. Such a structure is shown in Figure 27-16.

Almost every volcanic eruption is accompanied by huge amounts of gases that issue from the vent. These expanding gases—mostly water vapor from the magma pool—are what first cause the volcano to erupt. The vent is usually plugged up with solidified lava from the previous eruption. The pressure of the heated, expanding gas forces the plug upward. If the pressure is great enough, the plug will actually be shattered, and its fragments hurled skyward. The pieces may range in size from dust particles that may remain in the air for months, to huge boulder-size fragments weighing many tons.

The explosion of the volcano Tambora in the East Indies, in 1815, threw dust into the air in such huge quantities that for three days the sky was completely dark 300 miles away.

On the average, about 70 percent of the gas released during an eruption is water vapor. Other volcanic gases, such as sulfur dioxide, carbon monoxide, and hydrochloric acid, are poisonous and destroy life for many miles around the base of a volcano. Depending upon the viscosity of the lava, the gases

Figure 28-16 A lava tunnel at Rainbow Falls in Hilo, Hawaii

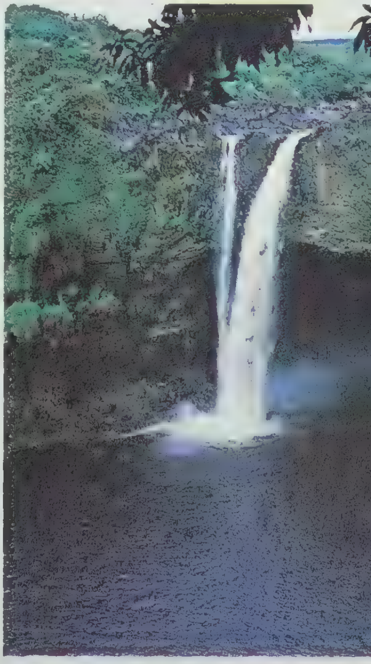


Figure 28-17 Ruins of St. Pierre, Martinique, after Mount Pelée exploded

will be released at different rates. If the lava is highly viscous, the gas will build up enough pressure within the lava flow to actually explode its way out. This is what causes much of the destruction that accompanies an eruption.

Martinique is a small, picturesque island in the Caribbean Sea. Just before 8 A.M. on May 8, 1902, a gigantic explosion ripped out the side of Mount Pelée, the volcano that makes up the northern end of the island. Below the volcano was St. Pierre, one of the island's ports, inhabited by 40,000 people. The explosion was caused by steam trapped under the plug in Pelée's neck.

Following the explosion, a fiery cloud of hot gases, some probably poisonous, accompanied by mud and lava roared down the mountainside. The temperature of the cloud was more than 1,500°F. The burning that accompanied it probably used up all the oxygen in the air. This combination of factors killed all but 2 of the 40,000 people in the city within minutes. The two survivors were prisoners who had been confined in a dungeon. Figure 28-17 shows St. Pierre the day after Pelée erupted.

A third type of volcanic ejecta is **ash.** Mount Vesuvius, the main vent in the caldera of Mount Somma, erupted A.D. 79. Hot ashes and huge **volcanic bombs** were hurled over the nearby towns of Pompeii and Herculaneum. A fiery cloud probably accompanied the eruption. These cities were excavated by archaeologists during the nineteenth century. The fourth type is boiling hot mud that gushes from either the main vent or the parasite cones.

Study Guide

1. List the four main forms of ejecta produced by volcanoes.
2. Explain how lava tunnels form.
3. Describe the difference between aa and pahoehoe.
4. How does the viscosity of lava affect the destruction caused by an eruption?
5. What is usually the first event in a volcanic eruption?

SUMMARY

The term *volcanism* is applied to many forms of igneous activity. These involve the formation and movement of magma at or near the surface of the earth. Volcanoes can either erupt violently or ooze quietly. The largest lava deposits are produced by the oozing type of volcano.

Volcanism is always associated with faults. We believe that some faults extend tens of miles into the earth's crust and mantle. At that depth, rocks that have been heated by radiation or by friction and pressure are at temperatures above their surface melting point. Release of pressure on such rocks causes them to melt and expand toward the surface through a fault or fissure.

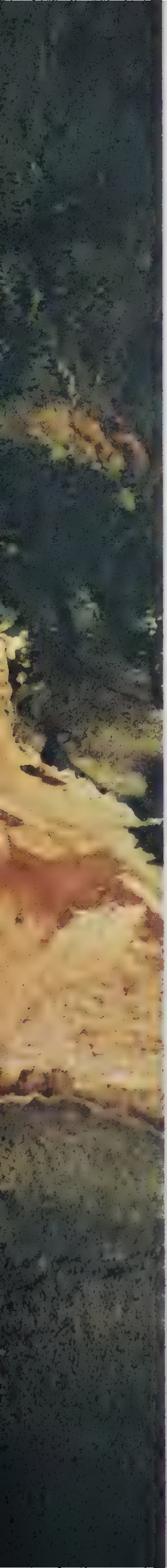
The material that pours out of volcanoes ranges from dustlike ash particles to viscous lava flows. Most eruptions are accompanied by large amounts of gases. Material that is intruded into sedimentary rock strata parallel to the strata is called a sill. Intrusions in a vertical position are called dikes.

REVIEW AND DISCUSSION QUESTIONS

1 To what does the term *volcanism* refer?
2. Define the following: ejecta, scoria, lava, crater, caldera, magma, volcanic plugs, dikes, sills.
3. Why might we consider Crater Lake to be misnamed?
4. How was the Valley of Ten Thousand Smokes formed?
5. Would you expect more future violent activity from a volcano that became dormant or from one that remained quietly active? Why?
6. Is there any possibility of violent volcanic eruption occurring in the future in the continental United States? Why or why not?
7. Distinguish between intrusive and extrusive volcanism.
8. What are the possible sources of heat energy produced deep in the crust of the earth?
9. What can be learned in the laboratory about temperature and pressure that applies to volcanic activity in the earth?
10. Using the thermal gradient of 50F° per mile, calculate the theoretical temperature at the center of the earth. Then explain why this could not possibly be correct.

CHAPTER 29

EARTHQUAKES



No matter how secure you feel about your surroundings, it is frightening to feel the ground tremble and to see trees and buildings shake. The relatively few earthquakes that are strong enough for us to feel are a small fraction of the thousands that occur each year. The majority of earthquakes are so mild that no one notices them, and they are recorded only by sensitive instruments. The eight or ten that cause severe damage in any one year are the exceptions.

29-1 WHAT IS AN EARTHQUAKE?

An earthquake results from anything that causes the rocks of the earth's crust to vibrate. Most large earthquakes occur because two large masses of rock slip a little along a fault. When vibrations are produced as these masses of rock rub against one another, we say an earthquake has occurred. Such an earthquake is called a **tectonic earthquake**. It is this kind that we shall study in this chapter.

There are several other causes of earthquakes. One of them is volcanic action. For a long time, scientists believed all earthquakes were associated with volcanoes. Now we know that this is not true. Most of the earthquakes that occur when a volcano is in eruption are tectonic.

Some earthquakes associated with volcanoes, however, are not tectonic. The gases dissolved in the hot magma expand with explosive violence when the magma approaches the surface of the earth. Such explosions shake the rocks and cause earthquakes. The rush of volcanic gases through underground passages and out of the volcano's vent may cause the rocks to vibrate. This vibration is very much like the flapping of a flag in a strong wind. The collapse of an underground chamber in a volcano may also cause an earthquake.

Man has produced earthquakes by setting off huge explosions. Many other man-made things cause vibrations of the earth that are felt for a short distance. A train rushing by may cause a microearthquake.

Effects of an earthquake on Montague Island, Alaska. A 15-foot uplift has exposed the ocean bottom, which appears as white.

29-2 WHERE DO EARTHQUAKES OCCUR?

No part of the earth is entirely free of earthquakes. Large areas of both the continents and the oceans experience occasional mild shakes that pass unnoticed. Earthquakes that we do notice are called *sensible* earthquakes; that is, we can sense them. Sensible earthquakes almost always occur where the earth's crust is unstable, that is, where mountains are growing or where volcanoes are active. This locates the most violent earthquakes around the perimeter of the Pacific Ocean, in the Mediterranean Sea and eastward to the Himalaya Mountains, and along the mid-ocean ridges (see Figure 29-1).

In North America the major earthquake area is its western coast, from southern Mexico to the western end of the Aleutian Islands. The Rocky Mountain region receives few sensible shocks. Occasionally, however, a damaging earthquake occurs in the vicinity of Yellowstone National Park. What might the existence of hot springs and geysers in that area mean?

The Midwest is almost without earthquakes, and along the East Coast only a few are noticed but many are recorded. Probably the great majority of earthquakes east of the Rocky Mountains are associated with **isostatic rebound.** This is the adjustment of the crust to the loss of the weight of the glaciers that once covered most of Canada and almost a third of the United States.

29-3 SOME FAMOUS EARTHQUAKES

Many severe earthquakes have occurred during the past several hundred years. From these we have selected three, each demonstrating an important feature. Each feature has helped build a theory that explains why earthquakes occur.

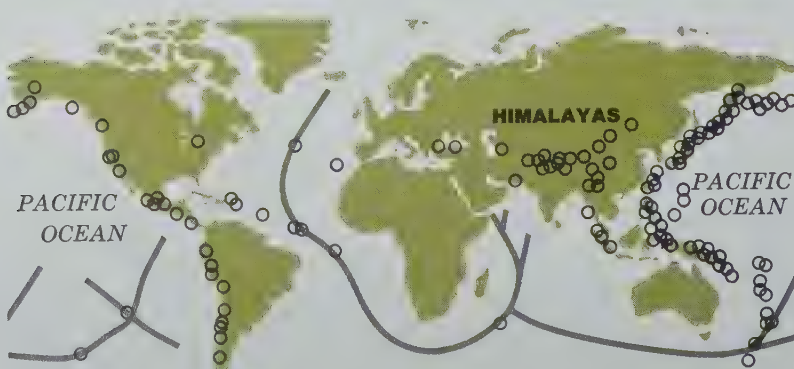


Figure 29-1 The major earthquake belts of the world

Probably no earthquake in recorded time has been felt over such a large area as the one that occurred in Lisbon, Portugal, early in the morning of November 1, 1755. The shock was felt over an area five times as large as the United States! Tens of thousands of people lost their lives, some as far as 400 miles away from where the earthquake originated.

A series of shocks completely devastated the city of Lisbon and killed about one fourth of its population. Some people were crushed by falling buildings, others were burned by the fires that swept the rocking city, and many were drowned by the huge wave of water that surged in from the bay.

The water 1,200 miles away in Loch Lomond, in Scotland, was tossed into waves several feet high by this earthquake. In Lisbon the shock forced the water out of the harbor, exposing the sea bottom. A wave was then thrown back as a wall of rushing water 50 feet high, which swept into the ruined city. A smaller wave raced across the Atlantic Ocean at several hundred miles an hour. This was an earthquake-induced tsunami (see Section 23-4).

On September 10, 1899, a severe earthquake shook the southeastern part of Alaska. Because it occurred in a sparsely populated area, it caused little damage. Investigators found that in Yakutat Bay the land had risen 47 feet, the greatest earth movement ever measured in association with an earthquake. It so disturbed the glaciers in the region that they advanced with unusual speed during the next few years.

Early on the morning of April 19, 1906, a severe earthquake struck the San Francisco Bay region of California. The city of San Francisco was shattered (see Figure 29-2), and the

Figure 29-2 The San Francisco earthquake of 1906 caused untold damage.

Figure 29-3 The San Andreas fault extends from the North Pacific Ocean through most of California and into Mexico. This map shows the areas where major earthquakes have occurred along the fault.

fires that broke out increased the damage. Cities a hundred miles south of San Francisco were seriously damaged. All these cities lie within the great San Andreas fault zone (see Figure 29-3). The surface of the earth was torn apart for 270 miles along that fault. On the Marin Peninsula, northwest of San Francisco, the land on the western side of the fault zone moved 21 feet northward with respect to the land on the eastern side.

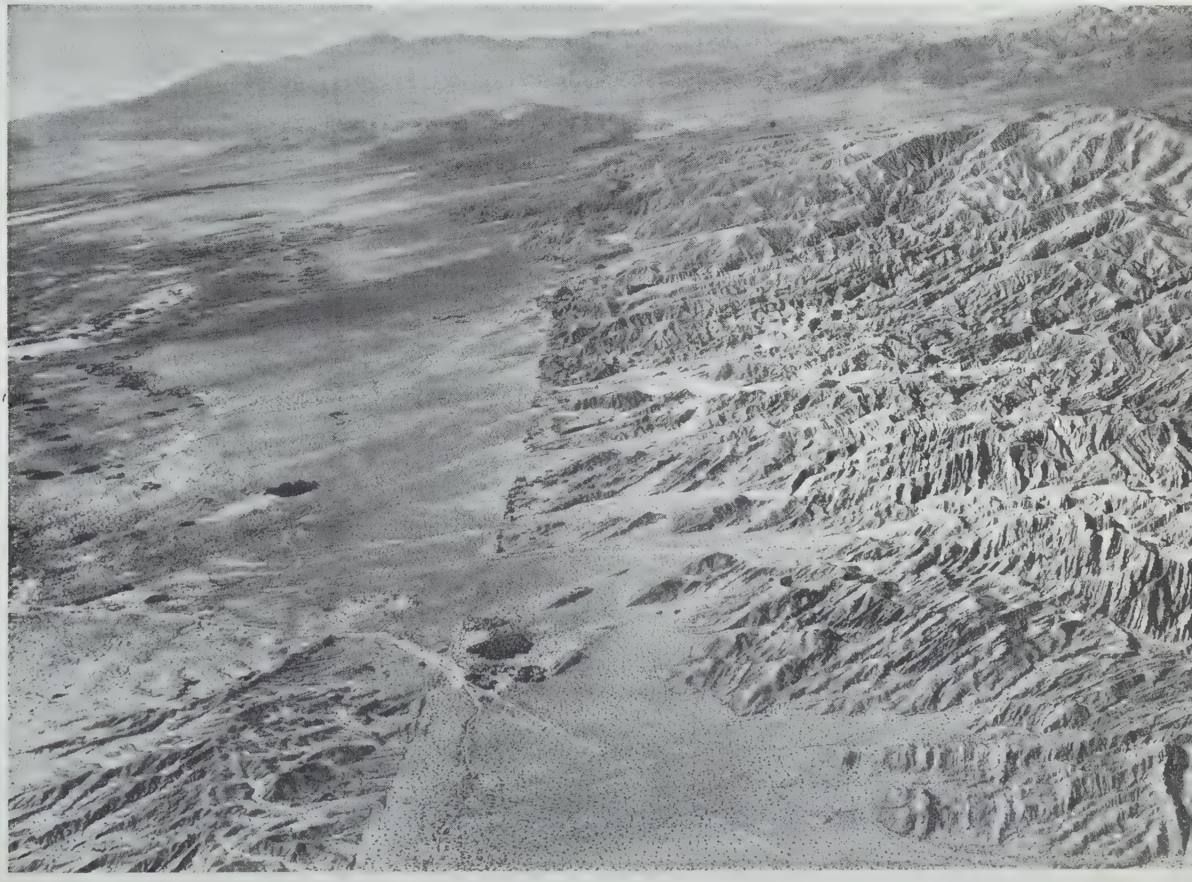
The San Francisco earthquake of 1906 probably did more to stimulate research into the causes of earthquakes than did any previous earthquake. It happened that the region had

been carefully surveyed before the catastrophe. This allowed scientists to accurately measure how much movement had taken place and to build theoretical models of the forces involved. Scientists were then ready to design and build instruments with which to study earthquakes.

29-4 THE ELASTIC REBOUND THEORY

Observation of what happens to the rocks at the surface of the earth during an earthquake clearly indicates that many earthquakes are caused by movements along faults. This was demonstrated at Yakutat Bay and along the San Andreas fault. In the Alaskan earthquake, most of the movement was more of less vertical, one huge section of rock moving upward with

Figure 29-4 A section of the San Andreas fault through the Indio Hills, Riverside County, California



respect to the other. In the San Francisco earthquake, the movement was almost entirely horizontal, one block slipping northward past the other.

Detailed studies of the movement along the San Andreas fault suggested that the western block—almost half of California south of San Francisco—had bent northward *slowly* over a period of from 60 to 100 years. The rough surfaces of the western and eastern blocks of the fault pressed against each other so forcefully that no movement occurred at the fault.

Instead, a great strain developed along the eastern margin of the western block. The surface appearance of the block was bent (warped) into a shallow S curve. When the stress that produced warping was sufficient to overcome friction along the fault, the edge of the western block snapped northward to relieve the stress. Stages of this series of actions are shown in Figure 29-5.

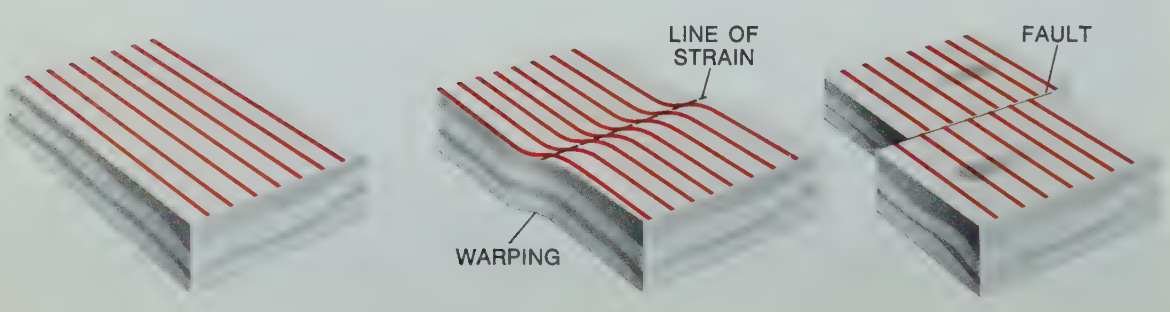
When the earthquake occurred, the strain was relieved almost instantaneously. The grinding of the two faces of the fault upon each other caused the rock of the two blocks to vibrate. These vibrations moved through the blocks, shaking everything that rested on them—trees and buildings alike. These vibrations are the earthquake that we feel.

The rest of the energy that you applied causes the wood to vibrate and to sting your hand. The vibration that stings your hand is a miniature equivalent of an earthquake.

If you bend a piece of wood in your hands until it snaps, you cause a stress great enough to exceed the strength of the wood. When the wood breaks, part of the energy you gave to the wood as stress tears apart wood fibers. The energy is converted to heat, and some sound—that is the snap (see note in margin).

Just before the wood breaks, the strain on it forces the straight piece to become curved. The curving is the *strain* in

Figure 29-5 The sudden release of strain that has been built up over a long period of time will result in an earthquake.



the wood that is caused by the *stress*. When the wood breaks, the stress and strain disappear, and the pieces are again straight. The ability of a material to return to its original shape, or rebound, after a stress has been applied and has been removed is called **elasticity**..

In the case of an earthquake, the stress disappears as a result of the movement of the rocks. The elasticity of the rocks then forces each of the blocks to rebound to its original shape. For this reason the modern theory of earthquakes is called the **elastic rebound theory**.

Study Guide

1. What does the word *elastic* mean when applied to solid materials such as rocks?
2. In what areas of the world do the most violent earthquakes occur? Why?
3. What probably causes the few earthquakes that occur east of the Rocky Mountains?
4. Describe how the Lisbon earthquake affected places far away.
5. What is the relationship between the earthquakes on the West Coast and the San Andreas fault?
6. Explain why there was no movement along the San Andreas fault as the western half of California south of San Francisco moved slowly northward.

29-5 MEASURING EARTHQUAKES

It has taken a long time for scientists to find a way to measure the forces involved in an earthquake. The first system was based on a scale of intensity invented by Giuseppe Mercalli, an Italian student of earthquakes. The scale ranges from I to XII. Intensities I to V are felt by an increasing percentage of the population. All people feel the shock of intensity VI. Objects are moved, and some plaster falls from ceilings and walls. Intensity XII indicates total destruction. With this crude scale, each earthquake is judged locally. The energy released by the shock cannot be accurately measured in that way.

Charles F. Richter, an American seismologist, invented a better scale, one that is related to the energy released by the earthquake. The Richter scale reports the magnitude of the earthquake. It is based on the record of the earthquake made by an instrument called a **seismograph**. The magnitudes are numbered from 1 upward. The record of an earthquake made

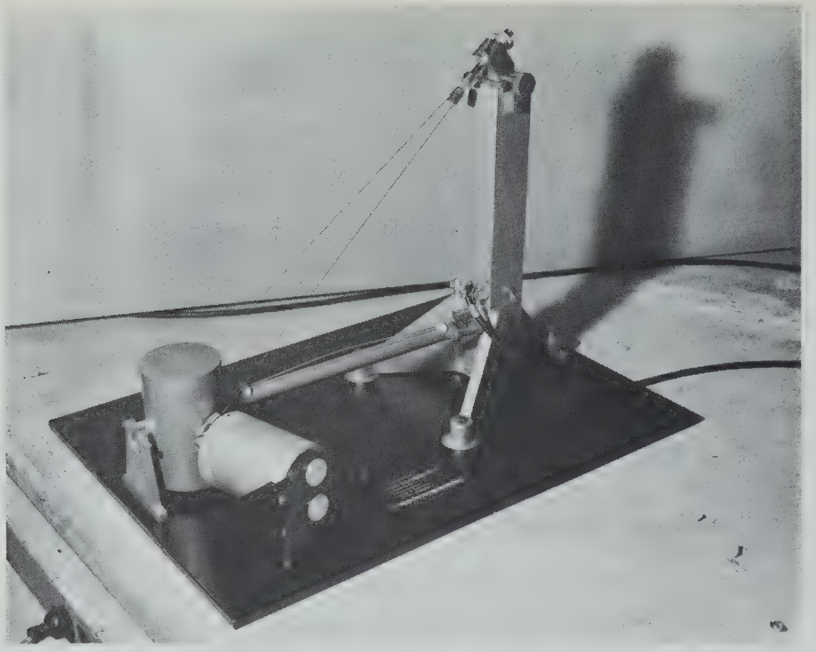


Figure 29-6 The horizontal-component seismograph is one type of seismograph used to detect earthquakes.

by a seismograph is shown in Figure 29-7. The magnitude is related to the amount the line is deflected. An earthquake of magnitude 2 makes a deflection 10 times as great as an earthquake of magnitude 1, and so on. Each magnitude number represents about 60 times the energy released by an earthquake one number lower. Thus, an earthquake of magnitude 5 releases 60 times as much energy as an earthquake of magnitude 4.

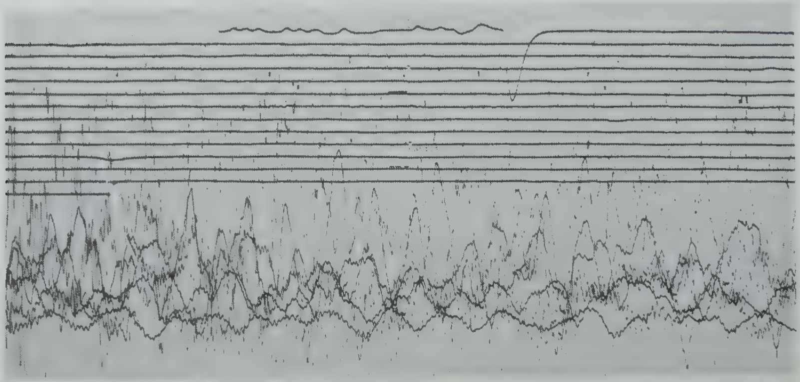


Figure 29-7 This seismogram shows the seismic patterns caused by the great Alaskan earthquake of March 28, 1964.

29-6 THE SEISMOGRAPH

The seismograph was invented by accident in the nineteenth century. In measuring the effects of tides on the earth, a group of German scientists found that their device was recording certain movements of the earth that did not seem to coincide with the tides. Eventually, they realized they had been recording earthquakes.

A simple seismograph consists of a heavy pendulum, which contains a marking device, and a revolving recording drum (see Figure 29-6). These two parts are not connected. The inertia of the pendulum prevents it from moving during an earthquake. However, the recording drum is attached to the bedrock, and so moves when the rock moves. Therefore, the marking device on the motionless pendulum marks on the recording drum the movements of the rock. Such a record is called a **seismogram** (see Figure 29-7).

A laboratory equipped to record earthquakes has at least three seismographs. One of these records the vibrations along a north-south line; another, along an east-west line. The third instrument, arranged in a slightly different way, records vertical movements of the crust.

29-7 RECORDING WAVES

When scientists first saw seismograms of an earthquake, they observed that the lines were complex. When there is no earthquake, the line is almost straight; there is usually some background vibration caused by traffic, machines, or other objects that cause vibrations. In the seismogram, the first indication of a distant earthquake is a little wiggle in the line. Following a short period of relatively little motion, there is another little wiggle, again followed by relatively little motion. One or more similar pairs of wiggles may follow, each separated by a quiet period. The amplitude of the wiggles then increases greatly, and this increased amplitude continues for some time.

amplitude (AM plu tood). In a pressure wave, the distance from the base line to the peak or trough.

Let us look at the simplest kind of record—two sets of low-amplitude wiggles followed by a set of larger ones. Figure 29-8 is such a record. The first wiggles are labeled "P-wave," which stands for **primary wave** (from *primus*, meaning "first"). The second set is labeled "S-wave," which stands for **secondary wave** (from *secundus*, meaning "second"). The large-amplitude wiggles are labeled "L-waves," (from *latus*, meaning "broad").

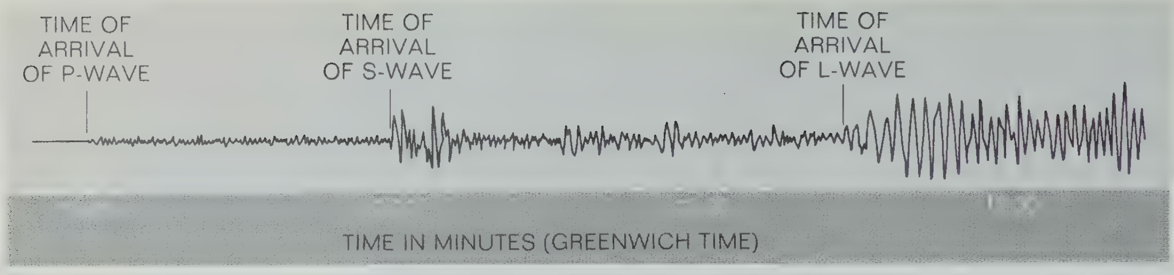


Figure 29-8 A record of P- and S-waves

29-8 INTERPRETING A SEISMOGRAM

It took scientists many years to understand what the lines of a seismogram meant. Geologists have come to the conclusion that the three kinds of waves recorded on seismographs—P, S, and L—report the arrival of three kinds of waves moving from the scene of the earthquake to the rock at the base of the instrument.

In Section 23-3 you learned about two kinds of waves that travel through matter. Shear waves are those that can travel only through a solid. Pressure waves can travel through liquids, solids, and gases. When physicists began to study earthquake waves, they used shear waves and pressure waves as mental models to explain the S-waves and P-waves on seismograms. Later they found that the S- and P-waves actually were shear and pressure waves.

A good example of a substance that is resistant to change in volume is water. Water can be used in a hydraulic jack to lift very heavy masses, because the water does not appreciably change its volume under great pressure. If you spill water, however, it spreads out in a very thin film, because the shape of a mass of water is very easily changed. Thus, water resists change in volume but not in shape. A steel bar resists both kinds of change.

Pressure waves and shear waves move through solids at different velocities. Pressure waves travel about twice as fast as shear waves. By using solids of uniform composition, experimenters found that three physical qualities of solids affect the speed of waves passing through them: (1) their resistance to change in volume; (2) their resistance to change in shape; and (3) their density. In all cases, the greater the resistance to change of volume or shape, the swifter is the velocity of the wave. An increase in density decreases the velocity of the wave.

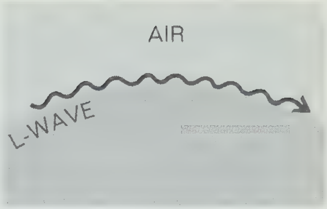
The last waves to arrive at the seismograph are the L-waves. These are complicated waves of long wavelength. L-waves travel at or near the surface of the earth. Here there are abrupt changes in the kinds of materials through which the waves pass. A sudden change in material, such as glacial till next to dense granite, is called a **discontinuity**. A place where two different materials meet is called an **interface**.

L-waves tend to travel along the interface of a discontinuity. Most important for the study of L-waves is the interface between the earth's surface and the atmosphere. L-waves that travel along the interface between the bottom of the continental mass and the lower parts of the crust have also been recognized and identified by scientists. Figure 29-9 shows where L-waves tend to travel.

As we have mentioned, the speed with which waves travel in the earth's crust varies with the kinds of rocks through which the waves pass. Table 29-1 shows how much variation has been discovered.

Table 29-1 Variation in speed of earthquake waves in the earth's crust

Wave type	*Speed near the surface*	*Speed deep in the crust*
P	5.5–6.0 km/sec	6.5–7.0 km/sec
S	3.3–3.7 km/sec	3.8–3.9 km/sec
L	2.0 km/sec	No wave



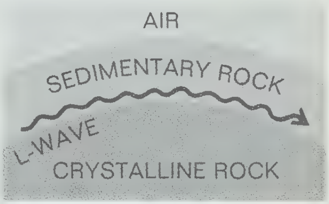


Figure 29-9 L-waves travel in the sedimentary layer below the crust and along the interface between the sedimentary and crystalline layers.

Study Guide

1. Explain two ways that isostasy may cause earthquakes.
2. What was the first system of measuring earthquakes based on?
3. Explain the basic principle of a seismograph.
4. What three kinds of waves are recorded by a seismograph?
5. What kind of wave travels the fastest through solids? Why?
6. What physical qualities of rock affect the velocity of the waves passing through it?

29-9 WHERE WAS THE EARTHQUAKE?

Usually, the first news about a distant earthquake disaster is a vague announcement. The news will report a seismologist saying something like this: "A severe earthquake occurred 2,000 miles from this station, probably in the Aleutian Islands." Later in the day, a more precise location for the earthquake is announced. How is the location found?

In theory there should be no difficulty in estimating the distance between the site of an earthquake and the seismograph that records it. We assume that P-waves and S-waves start from the earthquake site at the same time. From the seismograph record we can measure the difference in the time of arrival of the P- and the S-waves. We know, from information like that in Table 29-1, the difference in the speed

with which the two kinds of waves travel. From these data, the time the earthquake occurred can be estimated by the following equation:

$$T = S_v \ (S_t - P_t) \ / \ P_v - S_v$$

where T is the time it takes the P-wave to reach the seismograph.

Unfortunately, this easy way does not yield the correct distance. There are too many unknown factors in the problem. One that is quite obvious is the many different kinds of rock through which the waves pass. Through each of these rocks, the waves travel at a slightly different speed.

Seismologists have painstakingly gathered all the available records about accurately located earthquakes. This information includes when the earthquake occurred, when its waves reached each seisomograph, and the distance from the earthquake to each instrument. They have assembled this data into travel-time tables for each seismograph station. The information for one of these tables is plotted in graph form in Figure 29-10. Each station uses its own set of tables.

A travel-time graph shows the relationship between time and distance for each of the many kinds of earthquake waves. Our graph is simplified and shows only L-, S-, and P-wave travel times. Let us see how this kind of graph can be used to help locate the epicenter of an earthquake. The **epicenter** is the point on the earth's surface directly above the underground origin, or **focus**, of the earthquake.

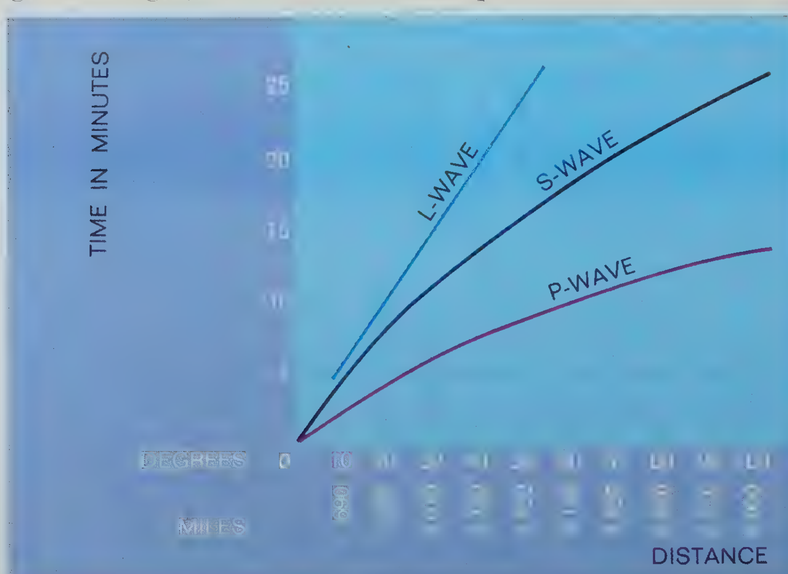


Figure 29-10 The distance and travel time of P- and S-waves

We can use this graph in an imaginary example. We will assume that exactly 4 minutes elapsed between the arrival of the P-and the S-waves. Take a sheet of paper with a straight edge. Place this edge near the time scale, which is the left edge of the graph. Close to the upper end of the paper, make a mark at 4 minutes on the time scale. Make another mark at the zero of the time scale.

Keep the straight edge of the paper parallel with the left edge of the graph. Move the paper so that one of the marks lies on the P line and the other on the S line on the graph. Be sure the edge of the paper is parallel with the left edge of the graph. Where the straight edge of the paper intersects the distance scale at the bottom of the graph shows the distance to the epicenter from the seismograph. You should read about 1,500 miles.

What does the 1,500 miles mean? It means that the earthquake occurred at some point 1,500 miles away from the seismograph. There is a circle of points 1,500 miles away. To determine at which point the earthquake occurred, we need more information. We can get that information from other seismograph stations. When the circles of distance from three or more stations are plotted, they will intersect near one point. A little triangle will be formed by the "near miss" of perfect intersection. The epicenter is somewhere in that triangle of error. In general, the larger the triangle of error, the deeper beneath the epicenter is the focus of the earthquake (see Figure 29-11).

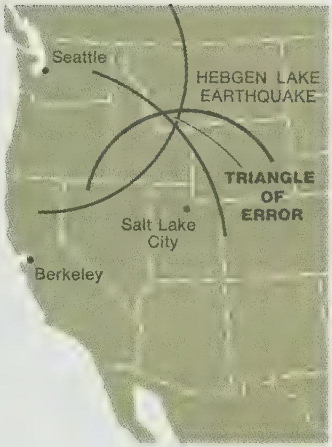


Figure 29-11 Arcs are drawn from major seismograph centers in order to locate the epicenter of an earthquake. The intersection of these arcs will form a small triangle of error and the epicenter of the earthquake will be located somewhere within this triangle.

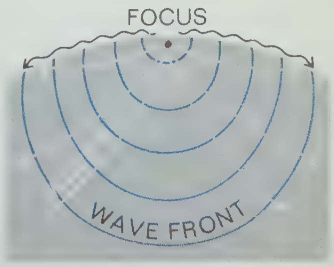
29-10 TRAVEL TIME FROM DISTANT EARTHQUAKES

Notice in Figure 29-10 that each line, L, S, and P, crosses the graph at a different angle. This is because each kind of wave travels at a different speed. The steeper the line, the slower the wave travels. Notice that the line for the L-wave is straight and is the steepest. It is the steepest because the L-wave is the slowest. It is straight because the L-wave travels through similar material all the way. Thus, it travels at a more or less uniform speed.

Look at the lines for the S-and P-waves. Both curve toward the corner of the graph. What does this mean about their speeds? It means that the longer the distance they travel, the faster is their average travel time.

Now look at Figure 29-12. There are two things to note. First, the longer the distance traveled, the deeper the wave ray must pass beneath the surface of the earth. Second, the

Figure 29-12 Wave rays move at right angles to any portion of the wave front. The wave rays bend as their velocity increases with depth.



wave rays (perpendicular to the wave front) are not straight but slightly curved. This curving is the result of refraction caused by rocks of different qualities. It appears from this that the deeper the rocks lie, the more resistant to change of form they are. Read Section 29-8 again if you need to review this.

From observed travel-time and distance measurements, scientists have concluded that earthquake waves bring us information about the interior of the earth. This is certainly worth investigating. We will do that in the next chapter.

Study Guide

1. What do we call the underground point where an earthquake originates?
2. Why are at least three seismograph stations needed to pinpoint the epicenter of an earthquake?
3. How can we estimate the distance between a seismograph and the point of origin of an earthquake?
4. Why does a sensitive seismograph never record a straight line?

SUMMARY

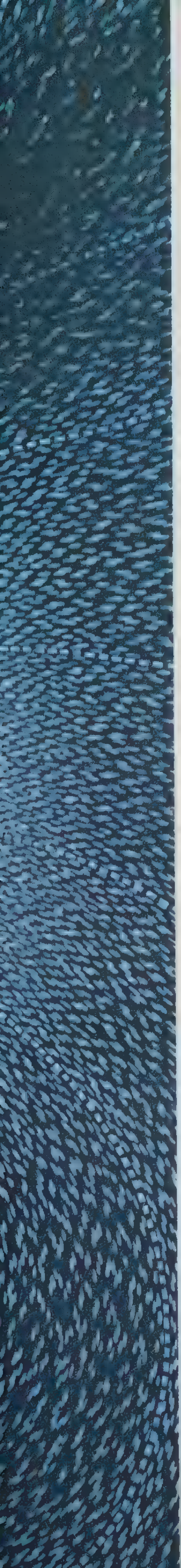
It appears that the majority of earthquakes are caused by the relative movement of huge masses of rock on two sides of a fault. The vibration produced by the friction of one block moving against the other radiates from the focus of the shock as pressure waves (P) and as shear waves (S). A third type of wave travels at or near the surface, where there is discontinuity in the materials. These are the long waves (L). The speed with which earthquake waves travel through rock is affected by the rock's resistance to change in shape, its resistance to change in volume, and the density of the rock. P-waves travel about twice as fast as S-waves. L-waves move most slowly.

By means of an instrument called a seismograph, scientists are able to locate the epicenter, and to a less accurate degree, the focus of the earthquake. The record produced by a seismograph also enables scientists to calculate the magnitude of an earthquake. Through study of seismograms, scientists have been able to form an acceptable model of the interior structure of the earth.

REVIEW AND DISCUSSION QUESTIONS

1. Why are unstable areas of the earth's crust subject to earthquakes?
2. Explain why a tsunami is caused by a P-wave and not an S-wave.

3. Describe stress and strain in terms of a balloon being blown up and breaking.
4. How might it be possible to predict a future earthquake at the San Andreas fault?
5. Explain the elastic rebound theory of earthquakes.
6. What is the relationship between the epicenter and the focus of an earthquake?
7. Why do P-waves travel faster than S-waves through rocks of the same type?
8. Using Table 29-1, estimate the distance from the seismograph to the focus of a shallow earthquake recorded with the P-wave arriving at 10 hr:24 min:13 sec and the S-wave at 10 hr:24 min: 39 sec.
9. An underground nuclear explosion is set off at exactly noon, Mountain Standard Time, in Frenchman Flat, Nevada. Using Figure 29-10, estimate the time of arrival (MST) of the P-wave at a seismograph 1,825 miles away.
10. Why may a severe earthquake in Chile, on the Pacific Coast of South America, cause considerable damage in Hawaii without the people there sensing the earthquake?



CHAPTER 30

THE INTERIOR OF THE EARTH

The interior of the earth has always been a great puzzle to scientists. While we do have some ideas about how the earth is constructed, we have very little evidence of what the earth is made of.

At the close of the nineteenth century, many geologists believed the earth was a solid sphere of granite or basalt or a mixture of the two common kinds of rock. This idea did not agree at all with estimates of the earth's density. Granite has a density of about 2.6 grams per cubic centimeter, and basalt about 3.0. Using modern methods, we estimate the average density of the whole earth to be 5.516 grams per cubic centimeter. This is almost twice the average density of the surface rocks—2.8 grams per cubic centimeter. It appears, then, that the earth is not a solid sphere of granite or basalt.

30-1 EARTHQUAKES AND THE INTERIOR OF THE EARTH

During the past half century, seismographs have been installed at many places on the earth. We have learned from these instruments that the elastic waves generated by large earthquakes travel completely through the sphere of the earth. We have also learned that the deeper the waves penetrate the body of the earth, the faster they move.

Figure 30-1 represents a part of the earth in cross section. The velocity of the waves is slowest at the surface and increases with depth (see Section 29-8). Therefore, the lines are not concentric around the focus. Notice that the rays curve toward the closest surface of the earth. The curved path of the rays is due to their refraction. The increasing density of the earth's interior causes the path of the rays to bend as the center is approached. There is one exception. The ray that passes from the focus directly through the center of the earth is not refracted.

The study of earthquake waves is solving the riddles of the earth's interior.

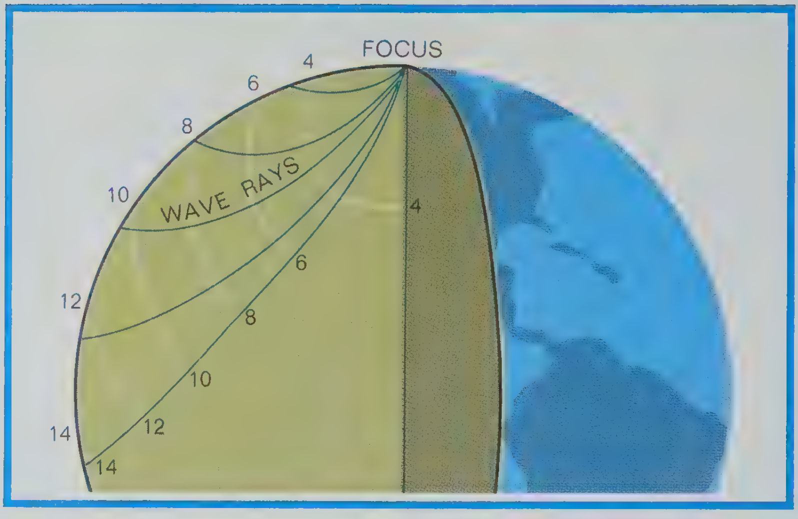


Figure 30-1 The best explanation of seismographic records is that the elastic-wave rays travel in curved paths concave to the earth's surface. The solid lines that radiate from the focus are wave rays perpendicular to the white lines, which indicate the number of seconds.

30-2 THE SHADOW ZONE

As scientists accumulated more and more accurate records of earthquakes, they became aware of a curious phenomenon. There is a zone, from about 102 degrees to about 143 degrees from the epicenter of an earthquake, where seismographs respond very little or not at all. Figure 30-2 shows the reason for such an area, which is called a **shadow zone**. From the epicenter to about 102 degrees away from it and from about 143 degrees to 180 degrees directly opposite the epicenter, seismographs produce good records of the shocks.

As soon as seismologists recognized the existence of a shadow zone, they began to build a mental model of the earth's interior to explain it. The path of the wave ray that emerges at a point about 102 degrees from the epicenter is of great importance. The wave ray curves in such a way that the greatest distance between it and the surface of the earth is never more than 2,900 kilometers. Something at that depth appears to interfere with rays that would curve deeper. Perhaps a major change in the structure of the earth occurs at that depth. Remember, such a major change is called a discontinuity. The part of the earth deeper than 2,900 kilometers is called the **core**.

Study Guide

1. What is the density of granite? of basalt?
2. What is believed to be the average density of the earth?
3. Why did geologists question the idea that the earth is a solid sphere of either granite or basalt?

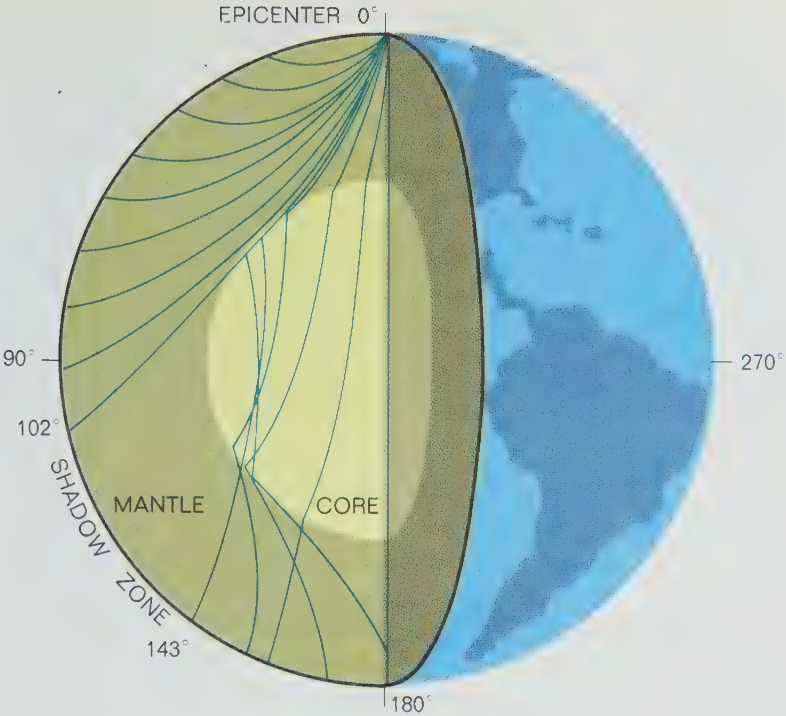


Figure 30-2 Something within the earth affects the earthquake waves that should be received by seismographs in a zone between 102 degrees and 143 degrees from the source of an earthquake. Why is such a zone called a shadow zone?

4. Why do waves follow a curved path from an earthquake?
5. What is a shadow zone?
6. What part of the earth is known as the core?

30-3 THE CORE OF THE EARTH

Careful study of seismograms recorded between about 143 degrees and 180 degrees from the epicenter reveal two important facts about the core. First, no S-waves appeared in the seismograms. To understand the importance of this, we need to recall the behavior of P-waves and S-waves in various substances. Both kinds of waves pass through solids because solids strongly resist both compression and change of shape. Liquids differ from solids in that they resist compression but their shapes are very easily changed. Therefore, P-waves will travel through a liquid easily. However, the speed with which P-waves pass through a liquid is much slower than their speed through a solid. S-waves do not travel through a liquid, because liquids lack resistance to change of shape.

The fact that no S-waves appear to travel through the core of the earth suggests that the core is not solid. This idea has been tested. If the core is solid, P-waves that pass through

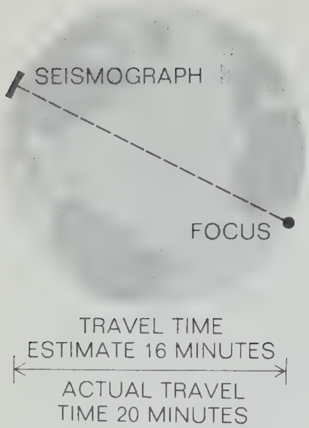


Figure 30-3 P-waves are slowed as they pass through the core, and S-waves are stopped by the core. The best explanation for such observations is that at least the outer core is fluid.

the center of the earth should reach a seismograph about 16 minutes after leaving the focus (see Figure 30-3). However, examination of seismograms of these P-waves shows that the actual time is about 20 minutes—4 minutes longer than expected. Therefore, the velocity of the waves through the core is lower than their velocity through solid rock.

The second important fact about the core is that only the outer portion is liquid. The inner portion seems to be solid. This conclusion is based upon travel times of wave rays that emerge at various points between about 143 degrees and 180 degrees from the epicenter.

30-4 THE MOHO

In 1909 a Yugoslav seismologist, Andrija Mohorovičić, discovered that seismograms of earthquakes with epicenters less than 800 kilometers from a seismograph showed pairs of P-waves and pairs of S-waves. He wondered why there were pairs of waves, as shown in Figure 30-4. His studies suggested to him that not too far below the surface of the earth there must be a discontinuity.

The effect that he observed and analyzed for earthquake waves is the same as that exhibited by light striking a piece of glass. As light rays pass from air to glass, some of the light is reflected, and some of it is refracted through the glass. Mohorovičić believed the second set of P- and S-waves had been reflected at the discontinuity, as shown in Figure 30-5. Seismologists called these reflected waves PP- and SS-waves.

Other seismologists examined other seismograms and found traces of PP- and SS-waves. The difference between the time of arrival of the second set of waves and the first set of waves enabled seismologists to calculate the depth at which reflection took place. On the average, the reflecting surface lies from 30 to 40 kilometers (18 to 25 miles) below the surface of the continents and from 10 to 12 kilometers (6 to 8 miles) below the surface of the oceans. This worldwide reflecting surface is called the **Mohorovičić discontinuity**, or the **Moho**.

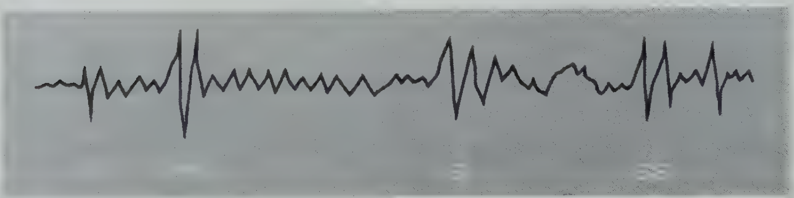


Figure 30-4 A seismogram showing pairs of P- and S-waves from an earthquake that originated less than 500 miles from the seismograph

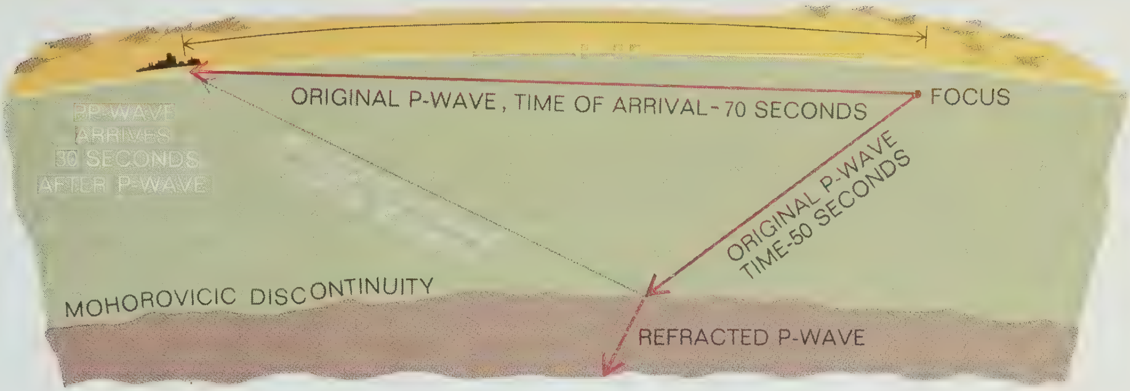


Figure 30-5 Some P- and S-waves travel directly from the focus to a seismograph. Others are reflected at a discontinuity and take a longer route from the focus to the seismograph, as illustrated here by the PP-wave.

Study Guide

1. What kinds of waves pass through solids?
2. What kind of wave passes through liquids?
3. How is the speed of a wave that passes through both solid and liquid affected by each medium?
4. What led Mohorovičić to believe earthquake waves are reflected at an area beneath the earth's surface?
5. What are PP- and SS-waves?
6. What is the Mohorovičić discontinuity?

30-5 THE CRUST AND THE MANTLE

Physicists have demonstrated that the Moho is a surface that separates rocks of different physical qualities. That part of the earth that lies above the Moho is called the **crust**. The crust is composed of the rocks that we know best—for example, the granites, the basalts, and the metamorphic and sedimentary rocks. In the crust, P-waves travel between 5.5 and 7.0 kilometers per second. In the region just below the Moho, P-waves appear to travel more rapidly—from 7.8 to 8.4 kilometers per second. The increase in velocity that takes place at the Moho must be caused by a change in the physical quality of the rocks.

Two physical qualities of matter that affect the speed of P-waves are density and compressibility. A lower density rock allows P-waves to increase their velocity. If the rocks below the Moho differ from those above only in density, the increased velocity of P-waves could be due to less dense rocks. We cannot accept this hypothesis because of the great overall density of the earth. Therefore, we must seek another reason.

The increase in velocity of P-waves must be related to an increase in resistance to compression of the rocks below the Moho. This region of more rigid rock that lies between the crust and the core is called the **mantle.**

30-6 THE CRUST

Rocks we see at the surface of the earth are varied. We know that at the surface sedimentary rocks, when present, cover crystalline rocks. Recently, oceanographic geologists have found the same thing to be true of the ocean bottom.

There is a difference between the most common crystalline rocks of the continents and those of the ocean floor. Continental crystalline rocks are rich in silica and aluminum. Ocean-floor crystalline rocks are rich in silica and magnesium. The continental rocks are called *sial*, from *si*lica and *Al*uminum. The oceanic rocks are called *sima*, from *si*lica and *ma*gnesium.

Sial rocks tend to be less dense than sima rocks. It appears that the continents are floating in sima rock (see Figure 30-6). Sial rocks also appear to be a little more easily compressed than sima rocks. The difference in compression, rather than the difference in density, has the greater effect on the speed of earthquake waves.

30-7 THE MANTLE

The composition of the mantle is still a mystery. We do have two observations that suggest the kinds of minerals and rocks that may exist there. For example, the lava of volcanoes on

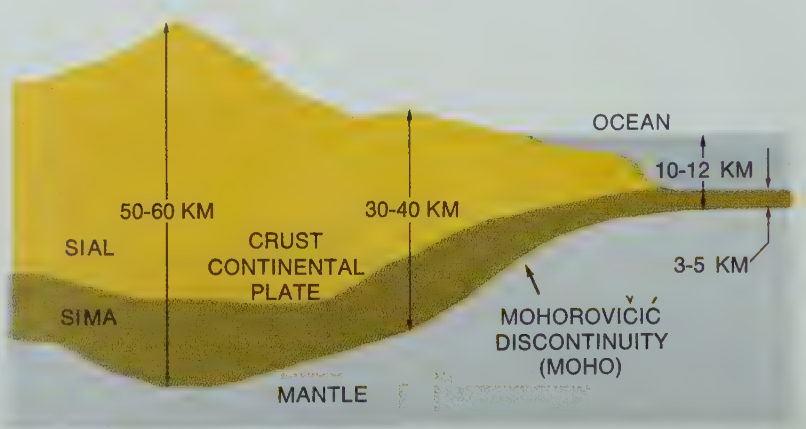


Figure 30-6 The study of seismograph records has shown that there is a layer of sima at the bottom of the earth's crust throughout the earth. The same records suggest that sial is confined to the continents. They also show that the crust is thicker under mountain ranges on continents and under the mid-ocean ridges.

the ocean floor may have been produced in the shallow crust, or it may be from magma pools in the upper part of the mantle. Samples of this lava have been recovered from dredge hauls in very deep water along the Mid-Atlantic Ridge and elsewhere. It is a basalt, but differs in some respects from continental basaltic lavas. One geochemical difference that may be important is that the deep-water basalts contain less than one tenth as much potassium as continental lavas.

Another observation is that the necks of a few old, eroded continental volcanoes contain rock that is quite different from basalt. This may be because the fault associated with the volcano reached into the mantle. These rocks are peridotites and dunites, very rich in iron-magnesium silicates. They are rarely found at the surface of the earth. The great diamond mines of South Africa and the far less productive ones in Arkansas are in peridotite volcanic rocks.

The travel time of earthquake waves in peridotite and dunite is faster than in the known crustal rocks. It is about the same as that in the upper mantle—about 8 kilometers per second. Geologists have used this kind of evidence in their attempts to learn about the composition of the upper mantle. It has led them to say that the upper mantle is probably composed of peridotite and dunite.

30-8 DRILLING FOR THE MOHO

A number of years ago a group of scientists suggested that a hole be drilled into the mantle to obtain samples. It was decided that the hole would have to be made at sea, where the crust is thinnest. A special drilling vessel was built, and a trial hole was drilled off the coast of Baja California, Mexico. The scientists learned much about deep-sea drilling, but the hole did not reach the Moho.

At present, plans are under way to build a vessel for another attempt to drill into the mantle. Not all the engineering problems have been solved. When and if the hole is drilled, we will learn what kind of rock is at the surface of the mantle.

Study Guide

1. What kinds of rocks compose the crust of the earth?
2. What are sial rocks? sima rocks?
3. Give two observations that suggest the kind of minerals and rocks that might be found in the mantle.
4. What kinds of rocks, though rarely found on the surface of the earth, are found in the necks of old volcanoes and in diamond mines?

5. In what part of the earth was the drilling for the Moho to take place? Why?
6. What information will a successful Moho project give?

30-9 EVIDENCE FROM TEMPERATURES

You have read how the study of earthquake waves was used to learn indirectly about the core and the Moho. There are other indirect ways of learning about the interior of the earth. For example, both P- and S-waves pass through the mantle. This means that the mantle is solid. This in turn means that the temperature at the bottom of the mantle is lower than the melting point of the rock.

What else do we know about temperatures inside the earth? From experience in mines and with drill holes, we know that the temperature of the upper crust increases with depth. The rate at which the temperature increases with depth varies greatly. It may be as high as 1C° per 27 meters (1F° per 50 feet) or as low as 1C° per 100 meters (1F° per 185 feet). If we use the lower rate, the temperature at the mantle-core discontinuity would be 29,000°C. Even under the great pressure at that depth, any known substance would melt and vaporize. Therefore, such temperatures can be ruled out.

Laboratory experiments with various kinds of rocks have tested the effect of pressure on their melting point. It seems that if the temperature at the bottom of the mantle were greater than 5,500°C, the rock there would melt.

Do we know anything about the crust and mantle that will explain why the temperature gradients are so different? Remember that oceanic basalt contains less than one tenth the potassium that continental basalt contains. Granite, the typical continental rock, contains much more potassium than either kind of basalt.

One of the isotopes of potassium, K-40, is radioactive. The decay of this isotope in the crust probably accounts for the high temperature gradient of the continental crust, where we have measured the gradient. We believe the mantle contains far less radioactive material than the crust. Therefore, in the mantle less heat is produced from that source. The mantle temperature gradient may be due almost entirely to the pressure of the overlying rock.

30-10 COMPOSITION OF THE CORE

What is the core material? We do not know. But we do know it must be a material that has a melting point lower than that

of peridotite. We know something else about it. It must be a substance considerably denser than peridotite. If it were not, the overall density of the earth would be much lower than it is.

We know a third feature of the core. The core material must be a substance that is abundant enough in the universe to have produced the core—about 3,400 kilometers in radius. What kind of material has all these properties: (1) a melting point lower than that of peridotite; (2) a density greater than that of any known silicate mineral; and (3) relative abundance in the universe? Only a metal satisfies the first two requirements. Look at Appendix V. You will see from that table that iron is the metal that satisfies the third requirement. Nickel might also be in the core.

30-11 A DENSITY PROFILE THROUGH THE EARTH

K. E. Bullen, an Australian geophysicist, has made the best estimates of the way the density of material varies from the crust to the core of the earth. Figure 30-7 is a graph of Bullen's estimates. At the surface of the earth, peridotite has a density of 3.3 grams per cubic centimeter. Notice in Figure 30-8 that the density of the mantle increases with depth from 3.3 to 5.8 grams per cubic centimeter. If the entire mantle is peridotite, why does its density increase with depth?

The deeper into the earth you go, the greater is the over-burden of rock and the greater the pressure. The fact that P-

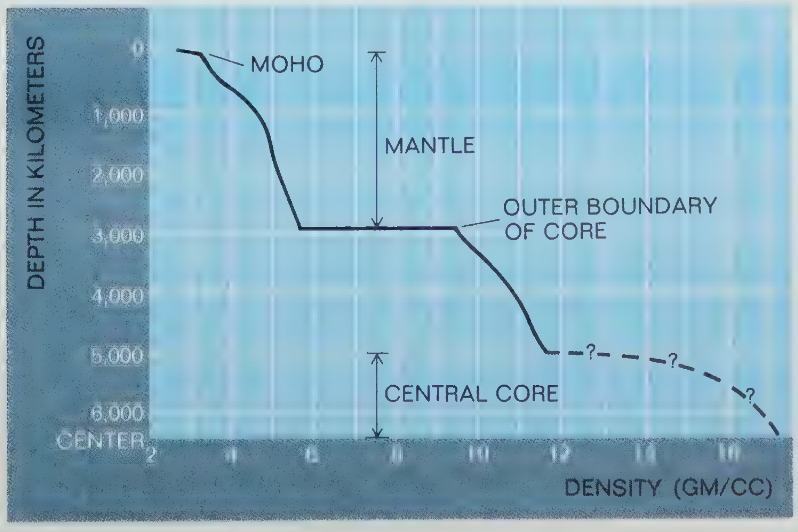


Figure 30-7 Bullen's density curve with depth in the earth is based on the behavior of earthquake waves.

and S-waves speed up as they penetrate the mantle also suggests increased pressure. The greater the pressure is, the more compressed the rock is. The more compressed the rock, the faster earthquake waves will move through it. If deep material is more compressed, it must occupy less space. This causes its density to increase.

Notice the very sharp change in density at the mantle-core boundary. This is where a very great change in material takes place. Bullen estimated that the density of the core at its boundary is about 9.5 grams per cubic centimeter. This is higher than that of iron at the surface (7.9). However, compression would increase the density at the mantle-core boundary. It is estimated that under the great pressure that must exist at the boundary, the melting point of iron is a little below 3,000°C. It is also estimated that the temperature at the mantle-core boundary is between 3,000°C and 5,500°C.

Thus, if the core is made up of iron, at least an outer zone of the core must be liquid. This is confirmed by the behavior of S-waves. They do not pass through the core. Seismograms suggest that the inner core is solid and begins at a depth of 5,000 kilometers. At that depth the pressure must be so great that the melting point of iron is raised above the temperature there.

Let us review Bullen's model of the earth (see Figure 30-8). It is a sphere with a core of iron, partly melted and partly solid, that is more than 3,400 kilometers (2,100 miles) in radius. This is surrounded by a solid mantle of rock, possibly peridotite, which is about 3,000 kilometers (1,875 miles) thick. The mantle is covered by a thin skin, the crust, rarely thicker than 60 kilometers (40 miles). Is there anything from the study of extraterrestrial bodies that gives support to this model of the earth? Yes, there are meteorites, and we shall study them in the next chapter.

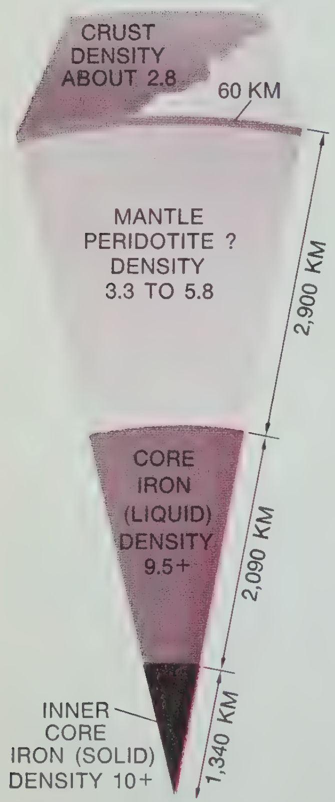


Figure 30-8 Model of the earth's interior showing the density of the crust, the mantle, the core, and the inner core

Study Guide

1. What are the sources of the information on which we base our ideas about the composition of the core of the earth?
2. Why do we believe heat is accumulating in the mantle?
3. How is the melting point of a substance affected as pressure is increased?
4. What can we logically assume about the density and temperature of the material that forms the core?
5. What do we believe the core of the earth is composed of?
6. Briefly summarize the structure of the earth based on Bullen's model.

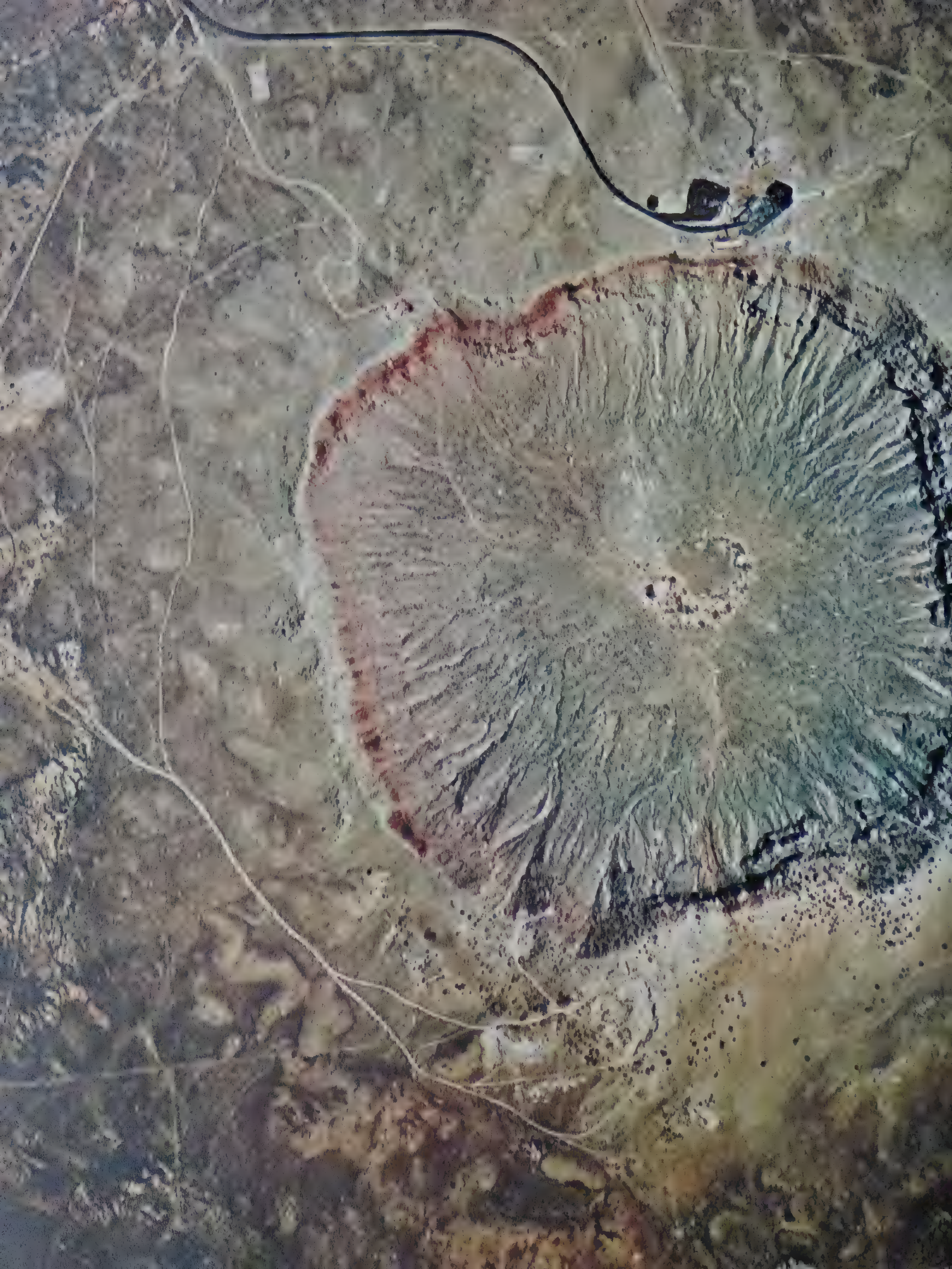
SUMMARY

The internal structure of the earth cannot be examined directly. All that we can do is build a mental model by using indirect information. The most important information that geophysicists have used in the construction of a model of the earth are the travel times of elastic waves produced by earthquakes. We believe the earth is composed of a very thin crust; a thick mantle, about 3,000 kilometers deep, possibly composed of peridotite or a similar substance; and a core of iron 3,400 kilometers in radius, which is partly melted and partly solid.

The density of material deep within the earth may be greater than the density of material at the surface. The temperature of the earth is believed to increase with depth to not more than 5,500°C and to be not much more than 3,000°C at the mantle-core contact. We believe radioactivity is producing heat within the crust faster than heat is escaping from the earth. This excess heat may be released by the earth through volcanism.

REVIEW AND DISCUSSION QUESTIONS

1. If the entire earth were composed of granite and basalt, how would the volume of these substances in the earth's interior be affected?
2. Explain the path followed by an earthquake wave.
3. What causes a shadow zone?
4. Explain why a shadow zone can exist anywhere on the earth.
5. How do shear waves and pressure waves differ?
6. How can we explain the fact that S-waves do not appear on seismograms made on the opposite side of the earth from the focus of an earthquake?
7. To determine the location of an epicenter, how many seismographic stations must record the arrival times of the earthquake waves?
8. Why do we believe the outer core is liquid instead of gaseous or solid?
9. What evidence indicates that the inner core is solid?
10. Why can the material composing the mantle not be less dense than the material composing the crust?
11. What kind of evidence is there to indicate that the bottom part of the crust is composed of magnesium silicates?
12. Why do we believe some continental faults reach the mantle?
13. What causes the extremely high temperatures we believe exist within the earth?
14. By what means is some of the internal heat released by the earth?



CHAPTER **31**

VISITORS FROM SPACE

You learned in the last chapter that there are many problems related to the interior of the earth. At the end of that chapter, we stated that meteorites give us some clue about the interior of the earth. Those of you who live in the country where there is little or no glare from city lights at night may have seen a meteor. They flash through the sky for a few seconds. Some people call them "shooting stars." They are not stars. Most of them are small fragments of material from space. A few are large. Let us see what we know about these visitors from space and how it helps us with the problem of the earth's interior.

31-1 METEOR CRATER IN ARIZONA

About 20 miles west of Winslow, Arizona, there is a curious natural formation. From the highway that passes to the north of it, it looks like a low, broad, flat-topped hill, a mesa. When you climb to the top of the hill, you find a surprise. Instead of a broad, flat summit there is a hole 600 feet deep and 4,000 feet in diameter, with only a narrow rim around it. The hole is deep enough to hide a 60-story building.

This curious depression was first brought to the attention of the scientific world early in the twentieth century by D. M. Barringer, a mining engineer. Early maps of the region, made in the late nineteenth century, called the hill Coon Butte. For several decades there were many arguments about the origin of this structure. Barringer believed the formation had been caused by a collision between the earth and a large meteor, an object from space.

The word *crater* always brings to mind a volcano. The depression in Coon Butte that Barringer thought had been formed by a meteor is deeply bowl-shaped, as shown in the photograph at the beginning of the chapter.

Figure 31-1 This view of Meteor Crater shows upturned layers of limestone and sandstone in the walls of the crater.

In the inner walls of the crater you can see thick strata of Kaibab limestone and Coconino sandstone. These layers of rock make up the bedrock of the Colorado Plateau, where the crater is found. These layers are almost horizontally bedded, but in the wall of the crater they are somewhat upturned. This is why the crater looks like a hill.

In the walls of the crater the limestone lies above the sandstone. On the outer slopes of the crater and in the rough ground around it, blocks of the sandstone lie on top of blocks of the limestone. This is the reverse of the order in which they were deposited. What may have caused this reversal?

If the crater had been caused by a volcanic eruption, then some evidence of it must be present. Careful examination of the debris scattered around the area shows there is a little volcanic ash present. There is also some in the bottom of the crater. This ash came from the eruption of Sunset Crater, some distance to the northwest, not from an eruption at the crater.

Another kind of material scattered about the vicinity of the crater is small pieces of iron. These pieces of iron show the wearing away characteristic of meteor particles that have landed on the earth, called **meteorites.** The presence of meteorites is evidence supporting the theory that the Arizona crater was the result of a collision between a meteor and the earth.

When you throw a heavy rounded stone on sandy soil, it forms a bowl-shaped dent in the sand. The impact throws sand up into a low ridge around the dent. An explosion that occurs a little below the surface of the ground also throws material out of the crater that is formed. In the rim of this crater and surrounding it, you find the material that was lifted and scattered by the explosion.

The material found at Coon Butte in Arizona shows that same reverse order. The material from the bottom of the disturbed area lies on top of material from the upper layers (see Figure 31-2). Thus, the crater at Coon Butte can be explained as one formed by an explosion caused by a collision between the earth and a meteor. Hence it is called Meteor Crater. Measurements of gravity in the crater indicate that far below the surface there is a mass of at least 3 million tons —possibly a sphere of iron 500 feet in diameter!

There are probably many meteor craters on the earth's surface. In the United States there is a small group of well-known craters at Odessa, Texas. In Canada numerous large and small craters have been found from the study of the aerial photographs used to map the country. One famous and very large one is in Ungava, the northwestern tip of Labrador. Some geologists go so far as to suggest that Hudson Bay may be an enormous meteor crater of very great age. Most geologists, however, believe Hudson Bay is the result of the glacial period.

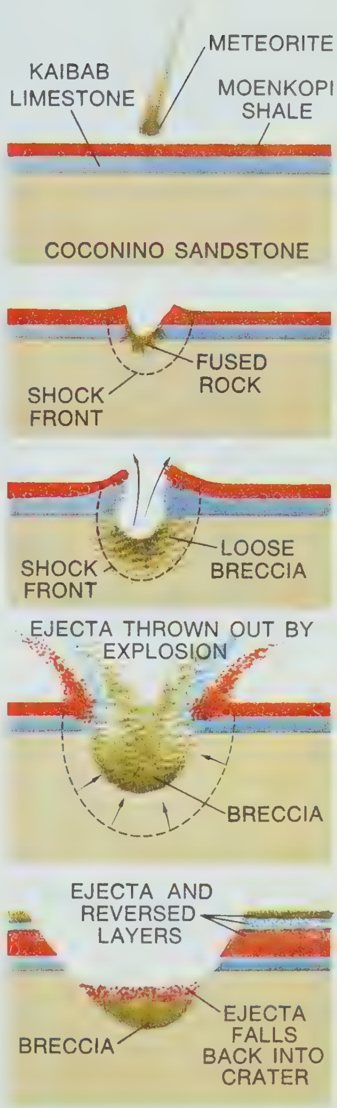


Figure 31-2 The order of reversed material around the rim of Meteor Crater. The broken fragments in the center are called *breccia*.

31-2 PARTICLES FROM SPACE

Meteors are masses of stone and iron from space that collide with our atmosphere and sometimes with the earth itself. Meteors vary in mass from less than a gram to thousands of kilograms.

Meteoric matter is continually entering our atmosphere, in amounts ranging from 1,000 to 10,000 kilograms daily. Only a few of these strangers from space are large enough to pass through the atmosphere and reach the earth's surface without being completely burned up. Those that have been found are called meteorites.

The composition of meteorites varies from almost pure (98%) metal, iron rich in nickel, to entirely stony material. The highly metallic kind are called **iron meteorites**, and the purely stony kind are called **stony meteorites**. The intermediate kinds, in which masses of stone are imbedded in metal or masses of metal in stone, are called **stony-iron meteorites**.

Figure 31-3 Students of meteorites cut and polish them in order to study their composition. *(Top, left to right)* Iron meteorite and cut-and-polished iron-nickel meteorite. *(Bottom)* Cut-and-polished stony-iron meteorite and cut-and-polished stony meteorite.

These types of meteorites are shown in Figure 31-3. The stony portion of meteorites is composed of crystalline olivine silicates.

The mineralogy of the stony parts of meteorites is interesting. It is just about the same as that of the basic igneous rocks found on earth—olivine and pyroxene. Some earth scientists believe the region of the earth immediately below the crust is composed of rocks rich in olivine and pyroxene. Some of the volcanic rocks on the surface of the earth also are rich in these minerals.

There are a few very odd stony meteorites. These are blackish granular masses, rich in carbon compounds. There has been a recent controversy over such meteorites. Some very able scientists believe these meteorites are bits of sedimentary rock. They also believe the carbon compounds were derived from life on another planet.

31-3 WHERE DO METEORITES COME FROM?

The origin of meteorites has been the subject of scientific study for many years. Two ideas about their origin have been

accepted by most scientists. First, most meteorites originate in our own solar system. Second, they probably have much in common with the belt of planetoids—small planetlike objects—that lies between Mars and Jupiter.

Harold Urey, of the University of California at San Diego, has spent many years studying the problem of the origin of the planets. He suggests that one kind of stony meteorites, called **chondrites**, may have been small masses of solar-system material that never had accumulated to form a planet. Chondrites contain tiny, rounded pieces of olivine or pyroxene, or both, embedded in an iron-nickel mass.

One theory, which has been popular for many years, was put forth by Richard Daly of Yale University. He believes meteorites are fragments of an exploded planet that once orbited around the sun between Mars and Jupiter (see Figure 31-4). He described the planet on the basis of the temperatures and pressures that may have existed when the stony parts of meteors were formed. His description takes into account the relative amounts of stony and metallic meteorites

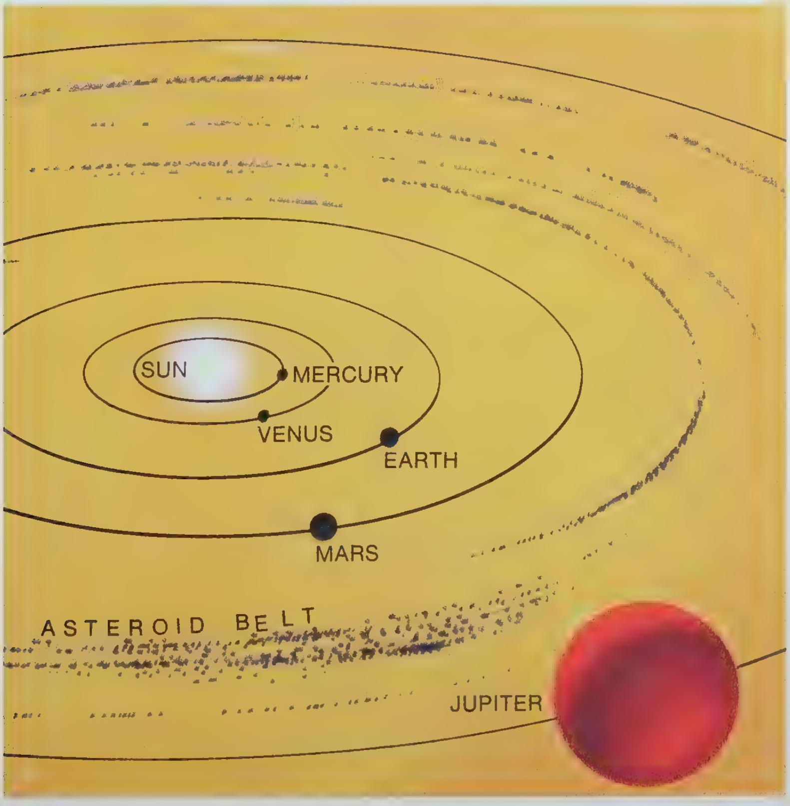


Figure 31-4 The asteroids, believed to be the remains of an exploded planet that was located between the orbits of Mars and Jupiter, range from tiny dustlike particles to giant boulders.

Figure 31-5 It was long thought that a meteorite caused the destruction of this Siberian forest. Now scientists believe a comet colliding with the earth was responsible.

that have been collected. He believed this planet was smaller than the earth. Therefore, gravitational force of the planet was less than that of the earth. For this reason the iron and the silicates were not so well sorted as they may be in the interior of the earth.

Meteorites have been dated by means of radioactive elements found in them. Most of them have been dated as being 4.5×10^9 years old. Some are younger. Recently, several scientists have suggested that meteors of different ages each resulted from the disintegration of a different planetoid at a different time.

Study Guide

1. How does the layering of the strata in the walls of Meteor Crater differ from the layering of the surrounding surface region?
2. What kind of evidence indicates the size of the meteorite buried within Meteor Crater?
3. What happens to most meteors that enter our atmosphere?
4. What is the basic composition of meteorites?
5. What is a chondrite?

31-4 ARE THERE OTHER VISITORS FROM SPACE?

On June 30, 1908, there was a great explosion over northern Siberia, between the Lena and Yensei rivers. A great flash of light accompanied the explosion. The blast blew down the pine forest for 40 miles around (see Figure 31-5). A year later,

when the site was studied by scientists, depressions up to 50 meters in diameter were found in the bogs.

Careful search failed to reveal any meteoric material. What had caused this catastrophe? No one really knows, but there is a clue. At that time a very small comet was close to the earth and has since disappeared. Did the head of that comet enter the earth's atmosphere and explode? Possibly this happened.

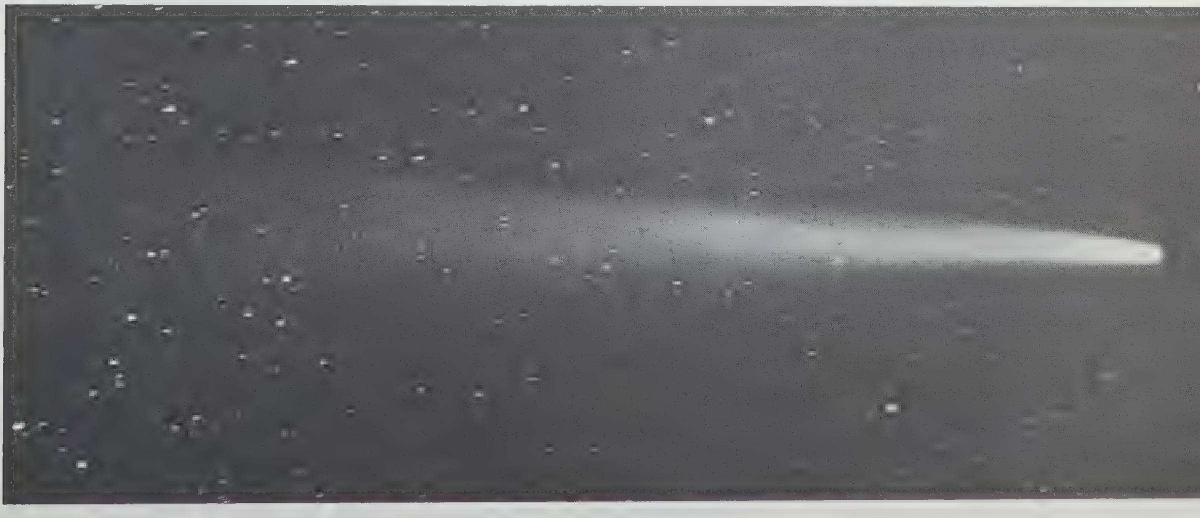
When observed through a telescope, a **comet** appears to be composed of a rather fuzzy glowing head and a thin glowing tail (see Figure 31-6). The tail is made of such light material that the force of radiation from the sun makes it stream away from the sun. Therefore, the head of a comet is always facing the sun.

We suspect that the bulk of a comet is frozen gaseous material. However, there is some evidence that the head may contain at least some particles that are much larger than single atoms or molecules. If such particles enter our atmosphere, they appear as meteors.

There are several meteor showers that occur each year. One that recurs each November, the Leonid, may be associated with a comet's path. These meteors get their name because they appear to stream from a point in the sky marked by the constellation Leo. The comet called Temple-Tuttle's Comet, named for its discoverers, is accepted as the parent of the Leonid meteor showers.

This comet loops around the sun every 33 years. Each year when the comet is closest to the earth, there is a particularly

Figure 31-6 The head of a comet is made up of a gaseous material surrounding a solid head. The tail of a comet is only visible when it enters the earth's atmosphere.



abundant shower of Leonid meteors. The last large shower was in 1965, when over a thousand meteors an hour could be seen.

Temple-Tuttle's Comet is the one that was reported by Chinese astronomers as early as 1366.

We do not know very much about comets other than the mathematics of their peculiar orbits around the sun. The orbits of the earth and other planets are elliptic paths that are almost circular. The orbits of comets are ellipses that approach a **parabola**, a path with one axis very much longer than the other.

From the above evidence it seems that there are two kinds of meteors. There are those that are sometimes large enough to reach the earth's surface. These probably originate in the planetoid belt between Mars and Jupiter. There are also those that seem to be associated with the paths of comets. It is not yet known which are iron and which are stony.

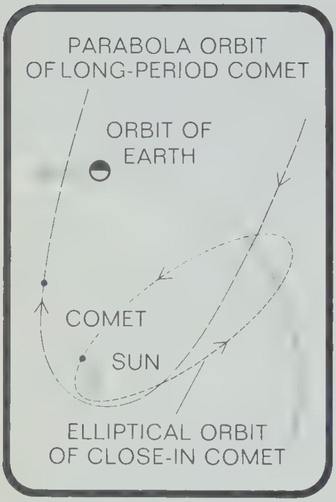


Figure 31-7 Astronomers have computed the paths of a sufficient number of comets to test the theory of their orbits.

31-5 GLASSY OBJECTS

Among other odd bits of material like meteorites that have been picked up on the earth's surface are **tektites** (see Figure 31-8). These are small, glassy objects. No one really knows where they come from. The glass of which they are composed looks like volcanic glass, called obsidian. Chemi-

Figure 31-8 Tektites probably originate somewhere in space. They are usually green or black in appearance and resemble some rocks of volcanic origin.

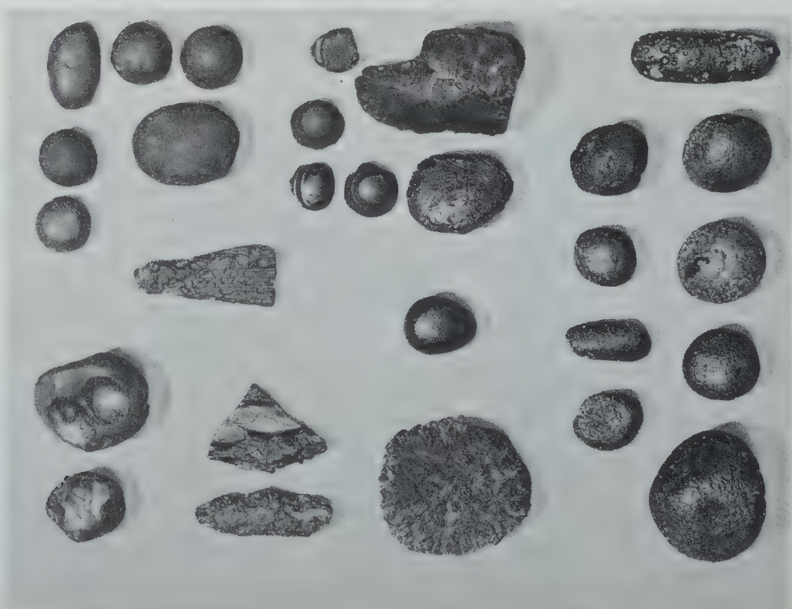


Figure 31-9 The "tektite fields" around the world

cally, it differs from obsidian. Some geochemists suggest that the glass may have been formed from melted granite or sandstone.

The peculiar thing about tektites is that they are found only over a few large but restricted areas—about half the state of Texas, for example. However, they are not numerous. A tektite longer than 5 centimeters (2 inches) is a good find. They vary in shape, but all are rounded. Some are dumbbell-shaped, others are more nearly spherical, and some are flattened.

In addition to Texas, there are several other areas noted for tektites. An area along the Danube River, in southeastern Europe, has been the source of many specimens. Perhaps the largest field of tektites extends from Malaya south to Australia and from the Philippines west into the Indian Ocean (see Figure 31-9). The discovery of minute tektites in the sediments from the bottom of the southern Indian Ocean was made in 1966.

31-6 WHAT IS THE SOURCE OF TEKTITES?

At present no one has satisfactorily explained the origin of tektites. A number of suggestions have been made. One of the suggestions is that tektites were splashed from the surface of the moon when a large meteor collided with it.

The tektites do show evidence of having passed through our atmosphere at high velocity. However, there seems to be no good reason for connecting them with the moon. If the

tektites came from the moon, they should show evidence of high heat twice in their lives—once when formed, and again upon passing through our atmosphere.

Thousands of tektites have been collected. Only those from Australia show evidence of having been melted twice. To explain this, some earth scientists suggest that at least some of the Australian tektites were blown so high that they passed out of the atmosphere of the earth. Falling back to earth, they were reheated upon entering the denser lower atmosphere. Thus, all but the Australian tektites suggest very strongly that these curious objects were formed at the surface of the earth.

Another explanation of tektites is that they are earth splash from a collision between earth and huge meteorites or comet heads. Using this hypothesis, Virgil Barnes, of the University of Texas, examined many of the regions where tektites are found. He also examined many of the known meteor craters. Impact-glass objects—very much like tektites—are sometimes found associated with large meteor craters. In several cases the tektite fields are near enough to the scars of old meteor craters to suggest that the two are associated. However, this is not true of the Texas tektites or the Australian ones.

In the case of the Texas tektites, the crater may be in the Gulf of Mexico or buried in sedimentary material. The Texas tektites are the oldest we know of. Potassium-argon dating places their age at 45 million years. Therefore, it is not surprising that evidence of a crater has disappeared.

The Australian tektites are the youngest known. They appear to be only 5,000 years old. Their crater may be in Antarctica, and they may have orbited the earth before showering Australia and the nearby Indian Ocean. That would account for the evidence of two periods of melting.

The moon-splash and earth-splash theories for tektites are not the only ones that are receiving serious thought. Bill Glass, of the Lamont Geophysical Laboratory of Columbia University, suggests that tektites may be the shattered and scattered remains of the head of a comet. If this is so, the collision may have caused a dramatic change on earth.

Glass and Bruce Heezen have found microtektites in cores of sediments from the Indian Ocean. At the same depth in the cores they found evidence of a drastic change in the magnetic field of the earth (see Section 32-8). They tentatively suggest that the tektites and the change in the earth's magnetism may have been caused by the same event. To understand this, we must next examine a recent hypothesis

used to describe the interior of the earth, magnetism, and drifting continents.

Study Guide

1. What may have caused the great explosion in Siberia in 1908?
2. What is the appearance of a comet?
3. What is the cause of the meteor shower that may be seen at night in November?
4. What does a tektite look like?
5. Give the two theories about the origin of tektites.

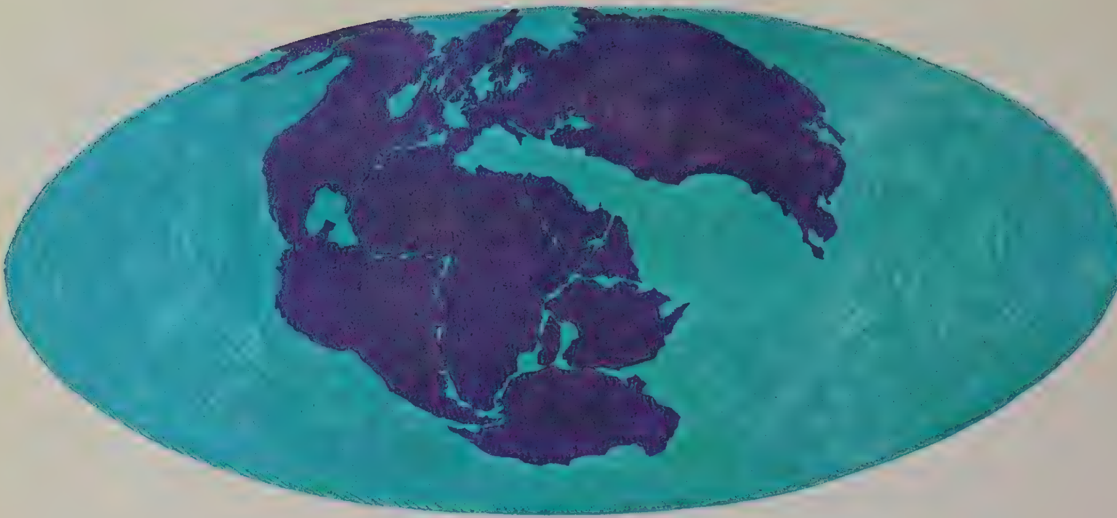
SUMMARY

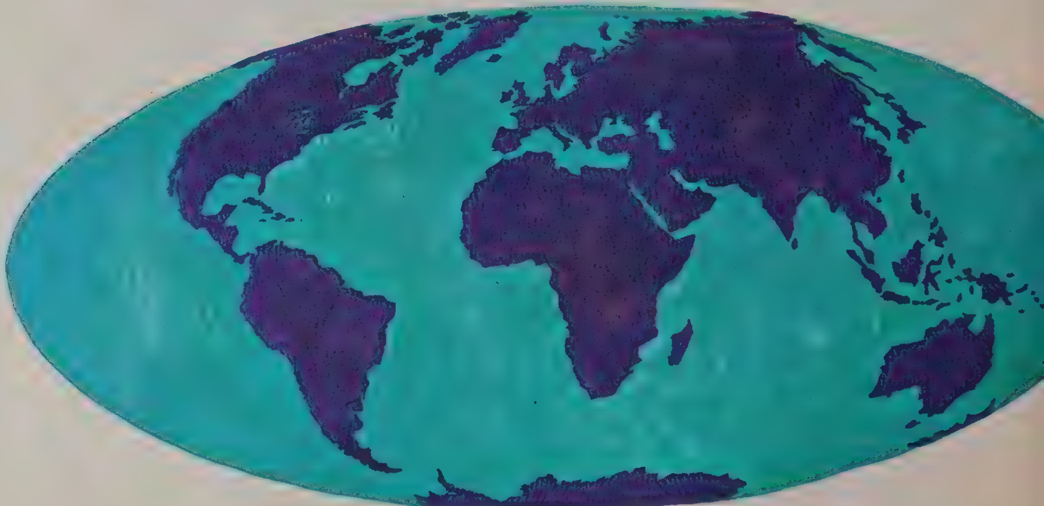
There is evidence that the earth collides with small objects from space. The clearest evidence that we have of these collisions is the space material itself, found after the collision. Such objects are meteorites. They may be almost entirely an alloy of iron and nickel, entirely stony, or a mixture of stony and metallic material. It is believed that the source of many meteorites may be a shattered planet. Other, smaller pieces may be fragments of a comet head.

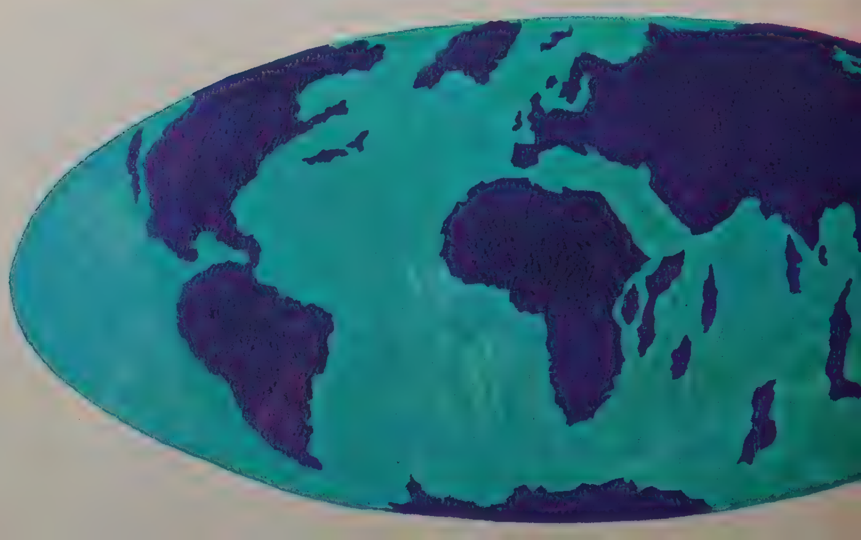
Another kind of object, tektites, may come from some extraterrestrial source, such as moon splash. Or tektites may be the splash of molten surface rocks of the earth caused by the collision of a meteor or a comet head with the earth.

REVIEW AND DISCUSSION QUESTION

1. Why could Meteor Crater not have been formed by erosion?
2. With meteoric material entering our atmosphere daily in great abundance, why are meteorites so hard to find?
3. Explain how iron meteorites differ from stony meteorites.
4. In what way do comets differ from all the other known bodies in the solar system?
5. What causes the earth to collide periodically with objects from space?
6. In which direction relative to the sun does the tail of a comet stream? Why?
7. What are the most generally accepted theories on the formation of tektites?
8. In what order are the materials thrown out by an explosion redeposited? Why?
9. What ideas have we deduced about the interior of the earth from the study of meteorites?
10. Why is the surface of the earth not so pockmarked as the surface of the moon?







CHAPTER 32

DO CONTINENTS DRIFT?

Throughout this book you have learned that there are many unsolved problems in earth science. Some of these problems have to do with the sources of energy necessary to perform the changes that we have observed or that we believe have occurred. For example, we do not yet know why there are glacial ages. We do know that since Precambrian time, parts of the continents have been covered with ice at different times. Today one whole continent, Antarctica, is ice-covered. This may be a normal condition in the polar regions. But Antarctica could not always have been ice-covered. It contains coal deposits rich in fossils of warm regions.

Perhaps the continents drift on the mantle and occasionally move into the polar regions. There they might become glaciated. Have we any evidence that the continents do drift? No, there is no direct evidence of this, but there are some facts that suggest that it might happen. Let us look into this problem of continental drift.

32-1 ALFRED WEGENER

Alfred Wegener, a German geophysicist, published a book in 1915 that caused about as much controversy as any book published in the earth sciences. In English it is called *The Origin of the Continents and Oceans.* Wegener believed that at one time in the past the continents of today were a single landmass surrounded by an ocean. He believed this huge mass of land broke up and the continents then drifted to their present positions.

The similarity of shape between the facing coasts of South America and Africa probably led Wegener to think about drifting continents. Look at a map or globe and see for yourself. Let us see what other evidence he found to support his hypothesis. During two expeditions to Greenland, in 1906 and in 1912, he calculated the longitude for two places. He

The continents may have originated as one huge landmass.

found that their longitude had changed. He considered this to be evidence that the two places must have moved. It was this idea that drove him to search for other evidence and to propose his hypothesis of continental drift.

Much of the evidence that Wegener presented in his book about continental drift is based on the present distribution of plants and animals on the continents. However, many of these data were incomplete. Later, scientists were able to explain the distribution of plants and animals by simpler ways than continental drift. For this reason, biologists lost faith in Wegener's hypothesis. Geologists could not accept the idea of continental drift because they could not find a source for the great amount of energy required to move the continents. Very recently, however, geologic evidence has been discovered that suggests that Wegener was right.

Wegener's calculations of longitude may or may not have been accurate. Since then it has been discovered, by using automatic devices to receive radio signals of time, that North America and Europe do move in respect to one another. During a period of 28 days they seem to drift apart and back over a distance of about 60 feet. This movement is the effect of lunar tides in the crust of the earth. The measurements used by Wegener can probably be explained by this back-and-forth movement. However, this is not the evidence for continental drift that he was seeking.

32-2 MODERN IDEAS ABOUT CONTINENTAL DRIFT

Today we believe that if continental drift does occur, it is so slow that we have no way to measure it directly. Therefore, we must look to indirect methods to support any hypothesis of drift. There are two kinds of continental drift to be considered. First, there is Wegener's kind of drift: the breakup of a single landmass into the present continents and the movement of the pieces to their present locations.

The second kind of drift is quite different: the entire crust of the earth shifts with respect to the poles of the axis of the earth (see Figure 32-1). It is as though the crust were floating on the mantle in such a way that it can slip over the mantle. Do we have any evidence that can be used to support either of these ideas?

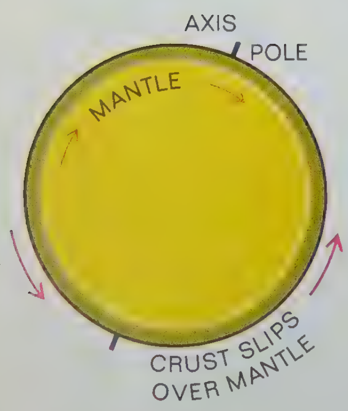


Figure 32-1 Perhaps the crust as a whole slides on the mantle. If so, we have not yet been able to measure the movement.

32-3 THE OCEAN RIDGES AND CONTINENTAL DRIFT

Scientists at the Lamont Geophysical Laboratory of Columbia University have been studying the Mid-Atlantic Ridge for several years. They believe the basin of the North Atlantic Ocean is very slowly getting wider. If this is so, Europe and North America are being pushed farther apart. What is the evidence for this idea?

These oceanographers have sampled the sediments on both sides of the ridge. The cores of sediments that they have raised tell them two interesting facts. The sediments at the bottom of the ocean get thicker as the distance from the ridge increases. The sediments at the bottom of the cores are progressively older as the distance from the ridge increases. How can this be explained?

If the entire floor of the North Atlantic Ocean is the same age, then sedimentation has been taking place over all the floor for the same length of time. If this is so, then there should be the same sequence and thickness of sediments wherever they are sampled. This was not found to be true. The ocean floor near the ridge appears to lack the thickness of sediments and the older sediments that are found farther away from it. Maurice Ewing, the director of the Lamont Geophysical Laboratory, has interpreted this as evidence that the floor of the North Atlantic Ocean is spreading eastward and westward from the ridge (see Figure 32-2). If the floor is spreading, where does the new floor material come from?

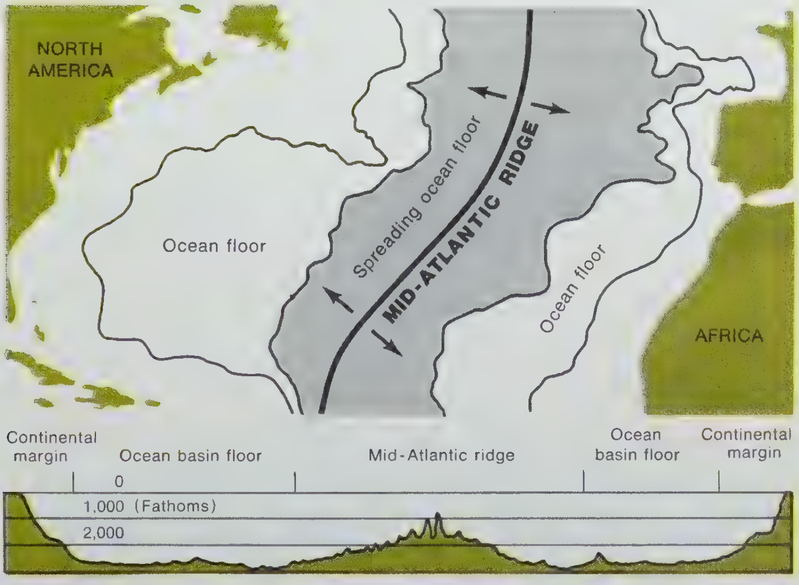


Figure 32-2 Ewing's ridge-expansion theory holds that the floor of the North Atlantic Ocean is spreading east and west from the Mid-Atlantic Ridge.

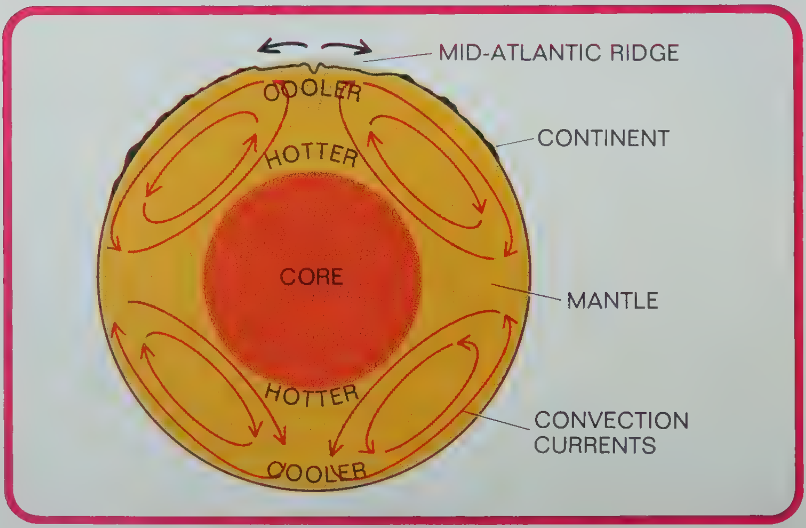
32-4 THE CONVECTION CELL HYPOTHESIS

To answer the question posed at the end of the last paragraph, we must consider a hypothesis about the mantle of the earth that is of interest to many geophysicists. This is the idea of convection cells in the mantle. When heat is unevenly distributed in a fluid, there is a regular pattern of circulation in the fluid. Such movement is called **convection**.

We believe the lower part of the mantle, which is in contact with the core, is considerably hotter than the upper part, which is in contact with the crust. If the mantle were fluid, there would be convection currents carrying heat away from the core to the crust and thence into space. Does such action take place in the solid mantle? We do not know because we have no way to observe such an action. Some scientists believe there is a very slow flow of material in the mantle, as shown in Figure 32-3. They believe that, rigid as it is, the mantle is plastic enough to flow slowly. If this is true, convection currents or cells in the mantle are possible.

A **convection cell** is composed of mantle material that moves upward from the bottom of the mantle. The mantle material then moves more or less parallel to the surface of the earth to a region where cooler material is sinking. Near the core there is movement to replace the material that rises.

Figure 32-3 The very slow movement of the mantle caused by convection currents may be responsible for building the Mid-Atlantic Ridge. If this theory is true, then the lower part of the mantle must be molten.



Because of the solidness of the mantle material, these movements must be very slow, possibly a few centimeters a year.

If convection cells really do occur in the mantle, their action may account for both the mid-ocean ridges and a spreading ocean floor. Those parts of the convection cells that are nearest the bottom of the earth's crust may exert a drag on the crust and cause it to move. This movement, if it occurs, probably is measurable only in millimeters per year. Where there is a stream of upward-moving material from the mantle, some material should be thrust upward. Are the mid-ocean ridges composed of that sort of material? We do not know.

As we have already mentioned, the basalt from the ridges appears to differ slightly from continental basalt. Gravity and seismic studies of mid-ocean ridges suggest that they are composed of somewhat lighter rocks than the underlying mantle material. It seems that the Mid-Atlantic Ridge, at least, is composed of this lighter material to a depth of about 30 kilometers.

32-5 WHICH WAY ARE THE CELLS MOVING UNDER THE RIDGE?

Experiments have been done in the laboratory with apparatus designed to imitate convection cells in the mantle. These studies show that a ridge is built no matter which way the material beneath the ridge is moving. Figure 32-4 shows how this happens. Two facts are important. (1) The material of the

Figure 32-4 The formation of a mid-ocean ridge and perhaps ocean trenches may be the result of convection in the mantle.

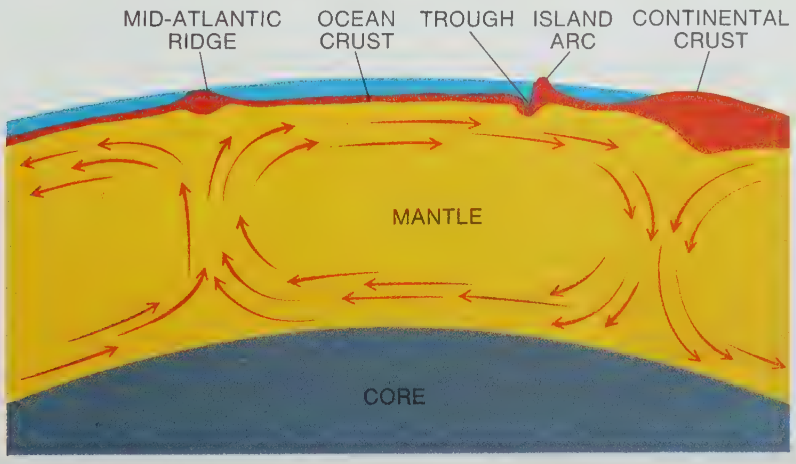
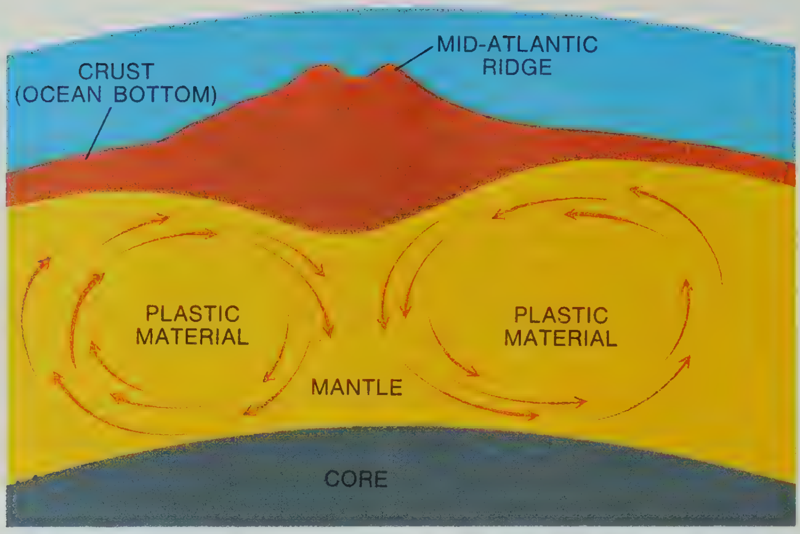


Figure 32-5 If the mid-ocean ridge lies over the downwelling of two convection cells, the material of the ridge appears to have been dragged to it from both sides. This would account for the depth of crustal rock beneath the ridge. However, it would not account for the increasing age of sediments as one moves away from the ridge.



Mid-Atlantic Ridge differs from the material of the upper mantle. (2) The ridge material appears to be similar to that of the thin crust under the rest of the ocean bottom.

Perhaps two cells are dragging together material from the bottom of the ocean crust to build the ridge, as shown in Figure 32-5. If this is so, one cell is dragging material eastward from the western part of the ocean and the other is dragging rock westward from the eastern part of the ocean. Where these two masses of dragged rock come together, a ridge may be pushed up.

Such movement would possibly affect the width of the ocean basin over millions of years. What would it do? It would make the basin narrower. However, the evidence from the cores suggests just the opposite. Thus far, what little we know makes it improbable that the ridge is composed of material dragged from the bottom of the crust.

Therefore, the action of the cells must be to spread the ocean basin, and the ridge must be composed of material that is welling upward from within the mantle. Possibly the small chemical difference in the composition of oceanic basalt is unimportant. Possibly the difference in the seismic response of the material of the ridge when compared with that of the upper mantle is caused by reduced pressure. These are things to be investigated and studied in the future. Today we do not know enough about them. Above all, we do not know whether convection cells really exist in the mantle.

Study Guide

1. What kind of evidence did Wegener use to support his hypothesis of continental drift?
2. Why did scientists lose faith in the idea of continental drift?
3. What do geologists at the Lamont Geophysical Laboratory believe is happening to the basin of the North Atlantic Ocean?
4. How does the age of sediments at the Mid-Atlantic Ridge compare with sediments to the east and west of it?
5. Explain how convection cells could produce a mid-ocean ridge and also widen the basin of the Atlantic Ocean.

32-6 DOES THE EARTH'S CRUST SLIP OVER THE MANTLE?

Early in this chapter we mentioned that a second kind of continental drift may be the entire crust slipping over the mantle. If such motion does take place, the continents could maintain their relative positions, or they could move about and slowly change their relative positions. Do we have any evidence that such slipping may have occurred? We do have some evidence that the magnetic poles have migrated in relation to the continents.

Before we can examine that evidence, we need to know something about the earth as a magnet. We know quite a bit about magnetism, but no one yet has proved how the magnetic field of the earth is generated. The compasses we use to determine direction respond to the lines of magnetic force that surround the earth. The recently discovered Van Allen belt of charged particles, which surrounds the earth in nearby space, is the result of the magnetic field of the earth.

32-7 MAGNETISM

When an electric current passes through a wire, a magnetic field is formed around the wire. When a loop of wire moves through a magnetic field, an electric current is produced in the wire. There is a specific relationship between the arrangement of the lines of magnetic force and the fact that in any magnetic field there are two opposite poles (see Figure 32-6).

In the case of the earth, we associate the names of the magnetic poles with the geographic poles, as shown in

Figure 32-6 Lines of magnetic force are stronger around the poles of a magnet than in the middle.

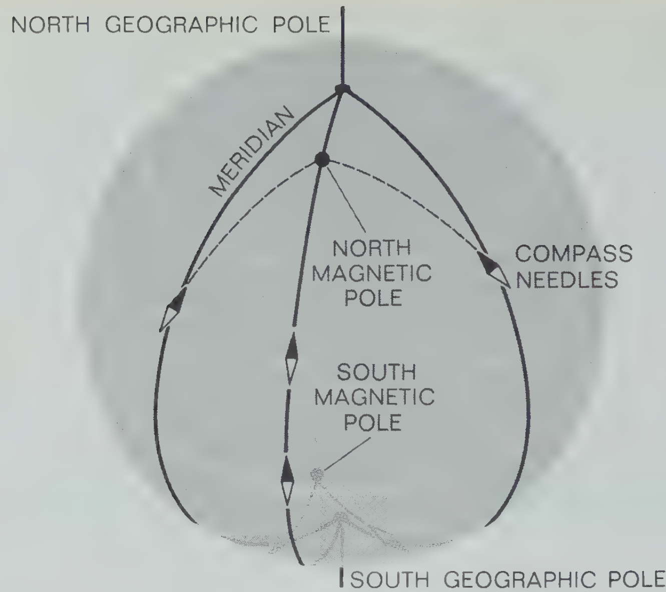


Figure 32-7 Polar projection showing the north geographic and north magnetic poles

Figure 32-7. Thus, we have a north magnetic pole and a south magnetic pole. One end of a compass is north-seeking, and the other south-seeking. Thus, the compass aligns itself parallel with the lines of magnetic force (see Figure 32-8). (You

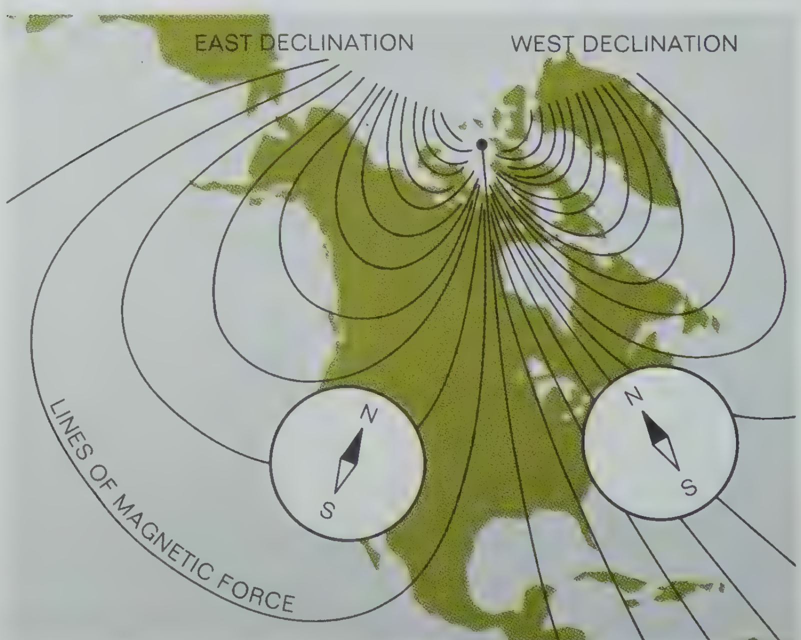


Figure 32-8 The lines of magnetic force are of equal declination in this figure. The compass needles align themselves parallel with the lines of force.

probably have learned all of this in earlier science classes and have seen much of it demonstrated.)

Many kinds of substances are affected by a magnet, but only a few are strongly affected. Of these, very few are found in quantity in the crust of the earth. One of these is magnetite, a mineral that is a complex oxide of iron. It is often strongly magnetized. There are other minerals that are less strongly magnetic.

Of all the substances that we associate with magnetism, iron is the most common. Soon after it had been proposed that the core of the earth is iron, some people suggested that the earth is magnetic because of that iron core. Unfortunately, they had overlooked two factors. First, the core is very hot, several thousand degrees Celsius. Second, iron looses its magnetism at around 800°C. Therefore, we cannot say that the earth has a magnetic field because it contains a huge magnetic core of iron.

The fact that a magnetic field is produced by a current flowing through a wire may be related to the flow of electrons from atom to atom on the surface of that wire. Some scientists have reasoned that since the core of the earth, at least in part, is fluid, there must be convection currents in it. Also, at the temperature we believe exists at the core, metals may be ionized. That is, the atoms of the metal may have an electric charge—there may be free electrons and ions. That would establish a magnetic field (see Figure 32-10).

Thus, after all, the magnetic field of the earth may be associated with its molten metallic outer core. There is absolutely

Figure 32-9 The magnetite crystals that are part of this piece of gneiss are aligned parallel with the lines of the earth's magnetic field.

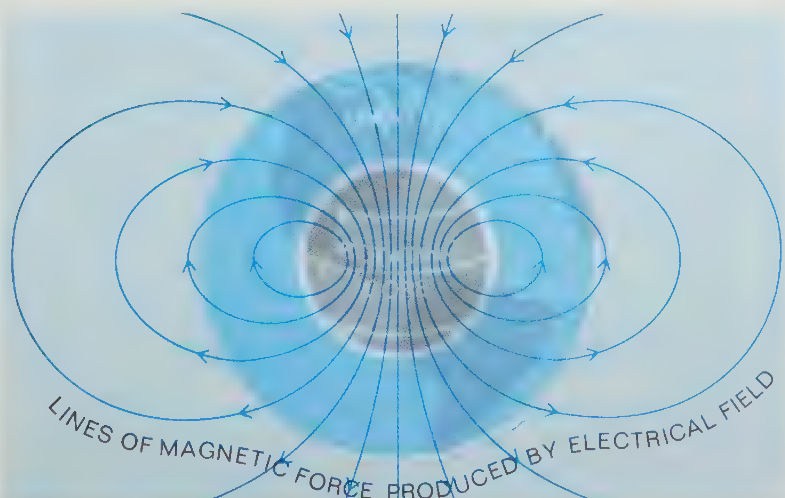


Figure 32-10 The outer core of the earth sets up a convection cell of flowing ions. This action is believed to be responsible for the earth's magnetic field.

no proof of this. It is just a hypothesis, which at present is untestable.

There is another hypothesis that is similar to the outer-core hypothesis. This is that a flow of electrons or ions in the convection cells of the mantle may be responsible for the magnetic field. If this is the case, we may be able to test it.

In a few parts of the world earthquakes occur with a focus at very great depth—around 700 kilometers below the surface. Such earthquakes may be caused by movement in the mantle. It is reasonable to believe the earthquake may momentarily affect the earth's magnetism under two conditions: (1) if the earthquake is associated with the moving edge of the cell; and (2) if the earth's magnetism is also associated with that part of the cell.

To test this idea, a geophysical laboratory has been built by the French government on an island near the Tonga Trench in the South Pacific Ocean, where such deep earthquakes have occurred. The scientists who man this station must wait until a deep-focus earthquake occurs.

One of the instruments being used near the Tonga Trench makes a continuous record of the earth's magnetic field. Another, of course, is a very sensitive seismograph. If the magnetic field is changed in any way at the time of a deep-focus earthquake, these instruments will record the facts. If a deep-focus earthquake alters the magnetic field during the quake, we will have some support, but not proof, for the hypothesis of convection cells in the mantle.

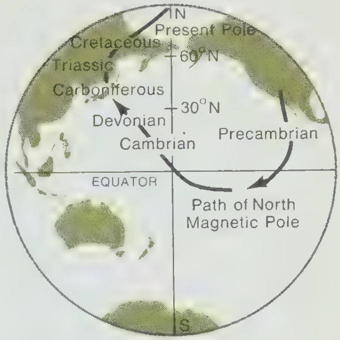
32-8 MINERALS AND THE EARTH'S MAGNETIC FIELD

Although we do not know why the earth has a magnetic field, we do know that such a field exists. Some time ago geologists recognized that when a rock is formed, its magnetite crystals, if any, are under the influence of the earth's magnetic field. These crystals should be aligned parallel with the lines of earth magnetic force. Study of such crystals in recently extruded lavas shows that this does happen.

However, studies have been of old lavas and of other old rocks that contain magnetite crystals. In these the crystals are *not* parallel with the present lines of geomagnetic force. This has been interpreted to mean that in the past the magnetic poles of the earth were located elsewhere.

Hundreds of measurements have been made on the orientation of crystals in rocks of different ages. This evidence suggests that at one time the north magnetic pole was some-

Figure 32-11 Magnetic measurements of rocks of many ages from the Northern Hemisphere suggest that the North Pole has migrated along the path shown.



where in the Pacific Ocean north of where Hawaii now is located. The rocks on which these measurements were made were formed in the early Paleozoic Era. During the Mesozoic Era the north magnetic pole appears to have wandered northward, near the Aleutian Islands (see Figure 32-11). During the Cenozoic Era it may have wandered still farther, until it reached Prince of Wales Island in northeastern Canada. That is where it is now. Many earth scientists feel that this hypothesis is open to serious question.

32-9 MAGNETIC POLE REVERSAL

Recent studies of the magnetism in rocks and sediments have revealed a startling possibility. The north and south magnetic poles may *reverse* periodically, and rather rapidly. Just what this new idea will do to our hypotheses we do not yet know.

The geophysicists who are working with this idea believe rapid changes in the rate of evolution of life may be caused by such reversal of the earth's magnetic field. During the period of magnetic pole reversal, they believe the magnetic field practically disappears.

If the magnetic field should disappear, the protection we now receive from the magnetosphere, which surrounds the earth, would also disappear. During that time the charged particles that now are trapped in the Van Allen belt would not be held far above the surface of the earth. More of this cosmic radiation would reach the surface. There it might bombard the germ plasm of plants and animals, causing many mutations (see Section 6-10).

This possibility that the magnetic poles may reverse periodically is so new that its implications have not yet been thoroughly studied. It is one more exciting problem to be solved by future earth and life scientists.

32-10 GLACIAL EVIDENCE

Glacial tillites—rocks formed from glacial tills—have been discovered among Precambrian and Paleozoic rocks (Permian in age). The latter are found in South Africa, South America, and Australia (see Figure 32-12). These areas of ancient glaciation have been used by scientists as evidence that the continents once were one great landmass.

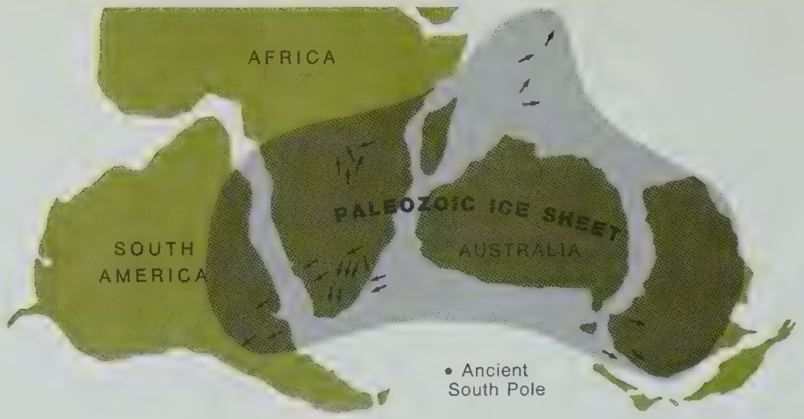


Figure 32-12 Some geologists explain continental drift by evidence of ancient ice ages in the Southern Hemisphere and the locations of the ancient South Pole.

The places where the tillites have been found are now warm regions. The scratches and grooves in the rocks and the morainal material that has been "fossilized" into rocks suggest a very curious state of affairs. They suggest that if the continents were then as they are today, the glaciers must have invaded the land from the oceans! Such a situation is impossible. The glaciers could not have formed on the oceans nor could they be anchored there. Without being anchored, the glaciers could not have pushed onto and across the land.

There are three ways that we can explain the Permian glaciations in the Southern Hemisphere. First, perhaps the geological evidence has been wrongly interpreted, and the glaciers did not move from the sea landward but from the land toward and into the oceans.

Another way to explain the observations of glaciations is that in the Permian Period land extended seaward far beyond its present boundaries. That would allow the glaciers to have anchorage and to move the way they are thought to have moved. However, what little evidence we have suggests this is not a good explanation.

The third explanation is that the glaciated areas were part of a much greater landmass in Permian time. A continental glacier may have existed over a region that has since split up and drifted apart, as shown in Figure 32-12. Those who believe in continental drift think that it satisfactorily explains these glaciated areas.

Study Guide

1. What is the most common substance found in the earth that is associated with magnetism?

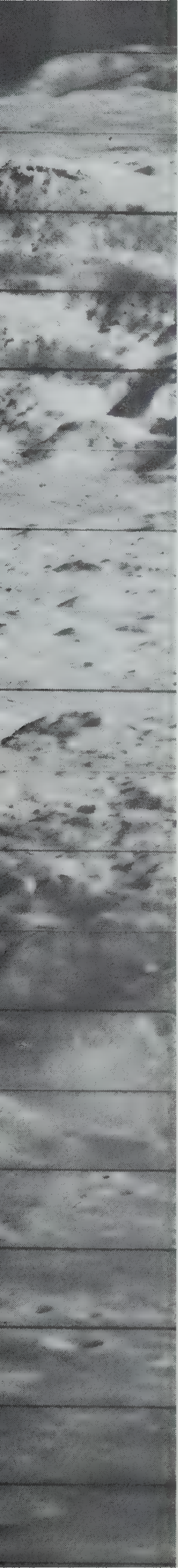
2. How does temperature affect magnetism?
3. Under what conditions might an earthquake affect the earth's magnetism?
4. What happens to magnetite crystals in recently extruded lavas?
5. What is the evidence from glacial tillites that supports the theory that the continents were once one landmass?
6. There is now evidence that evolution of life may sometimes occur very rapidly. What do some geophysicists believe may cause this rapid change?

SUMMARY

There is evidence that continents do drift. This drift must be very slow. The continents may be moving away or toward each other, or the entire crust may be slipping over the mantle. We do know that the magnetic poles seem to migrate. The problem of continental drift appears to be bound up with the problem of why the earth has a magnetic field. There are no wholly acceptable solutions to either of these problems with the limited knowledge that we have today.

REVIEW AND DISCUSSION QUESTIONS

1. What led Wegener to propose his idea of continental drift?
2. What might variations in longitude at any one place indicate?
3. What kind of data did the scientists at the Lamont Geophysical Laboratory obtain to support the idea of continental drift?
4. If rock crystals with strong magnetic tendencies are not aligned parallel with the present lines of geomagnetic force, what is indicated?
5. Explain the convection cell theory.
6. List the sources of evidence for continental drift.
7. How far back in time has the earth been subjected to occasional glaciation?
8. Under what circumstances would the magnetic field of the earth be almost nonexistent? What would this have to do with the rate of evolution of life?



CHAPTER **33**

THE MOON AND THE SUN

The moon is our nearest neighbor in space. It is a satellite of the earth and has been orbiting for several billion years according to most estimates. In turn, the earth is a satellite of a star we call the sun. This relationship has existed ever since the earth was formed. The sun supplies us with light and the energy with which plants manufacture the food that supports life on the earth. You already know something about the work done on the earth by energy from the sun.

Because the moon is our nearest neighbor, it is the first target for a visit in space by man. We have landed unmanned probes on the moon, and we may soon land a man on the moon. The first astronauts to walk on the moon will be highly trained in the earth sciences. They will be well trained particularly in geology, because the moon lacks oceans and because its atmosphere may be nonexistent. You should know what has been learned by man's ingenious study of the moon from a quarter of a million miles away.

33-1 THE PHASES OF THE MOON

Probably one of the first observations man made about the moon was that it does not shine every night. When it does shine, its shape appears to change from night to night. If you see the moon close to the sun at sunset, it appears as a thin crescent (see Figure 33-1). We call this a **first crescent moon**. Each night thereafter, the moon appears farther east of the sun, and the crescent thickens. In about a week the moon is about half way between east and west at sunset in the Northern Hemisphere. We then see the western half of the moon's disk illuminated by sunlight. We call this phase of the moon a **first quarter moon**. On a clear night at this time, the eastern half of the moon is sometimes faintly visible, illuminated by light reflected from the earth, called earthshine.

Lunar Orbiter II's closeup view of the lunar surface shows the crater Copernicus, which is 60 miles wide and 2 miles deep.

Figure 33-1 The period from new moon to full moon, when the light reflected by the moon grows in intensity, is called *waxing*. The period from full moon to new moon is called *waning*.

About two weeks after the first crescent moon, the moon rises in the east just after sunset, and its full disk is visible by reflected sunshine all night. This is the **full moon**. From then on, the moon rises nearer and nearer to the time of sunrise and the moon's illuminated surface diminishes in area. When only the eastern half is lighted by the sun, the moon is called a **last quarter moon.** Finally, when the moon and the sun rise at the same time, the dazzling light of the sun obscures the moon. This phase is called the **new moon**. The positions of the sun, the moon, and the earth during the various phases are shown in Figure 33-2.

The interesting thing about the moon as it passes through these phases is that we always see the same features on its surface. The same side of the moon always faces us. This is because the moon makes one revolution around the earth in the same time it makes one rotation around its axis.

We now know that the unseen part of the moon resembles the side we can see. First the Soviet Union and then the United States sent space probes to orbit the moon. The cameras they carried televised back to earth many photographs of the hidden side of the moon.

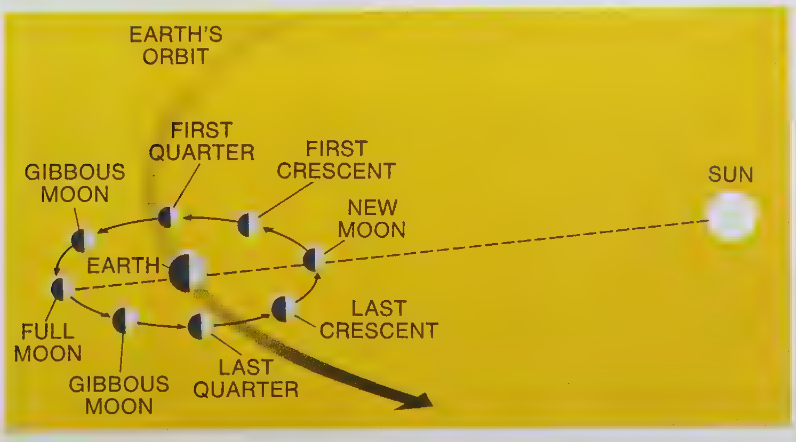


Figure 33-2 Changes in the relative positions of the sun and moon as the moon orbits the earth are responsible for the phases of the moon.

33-2 HOW FAR TO THE MOON?

How do we measure distances on the earth? The simplest way is to use some sort of measuring stick or tape. Obviously we cannot use this method to measure the distance to the moon. Surveyors use another method for measuring long distances which involves a triangle. They measure the length of one side of the triangle and the adjacent angles of it. From these data, they can calculate the length of the other sides of the triangle (see Figure 33-3).

Astronomers can use a similar method for measuring the distance to the moon. The base of the astronomer's triangle is the straight-line distance between two earth observatories from which the moon can be seen at the same time. For instance, two such observatories might be in New York City and in Quito, Ecuador. At each observatory astronomers observe the angle between the moon and the horizon at a known time. Knowing these angles and the straight-line distance between the two observatories, they can compute the distance to the moon.

The best estimate we have is that the moon is about 80.267 earth radii away. In more familiar units, the moon is about

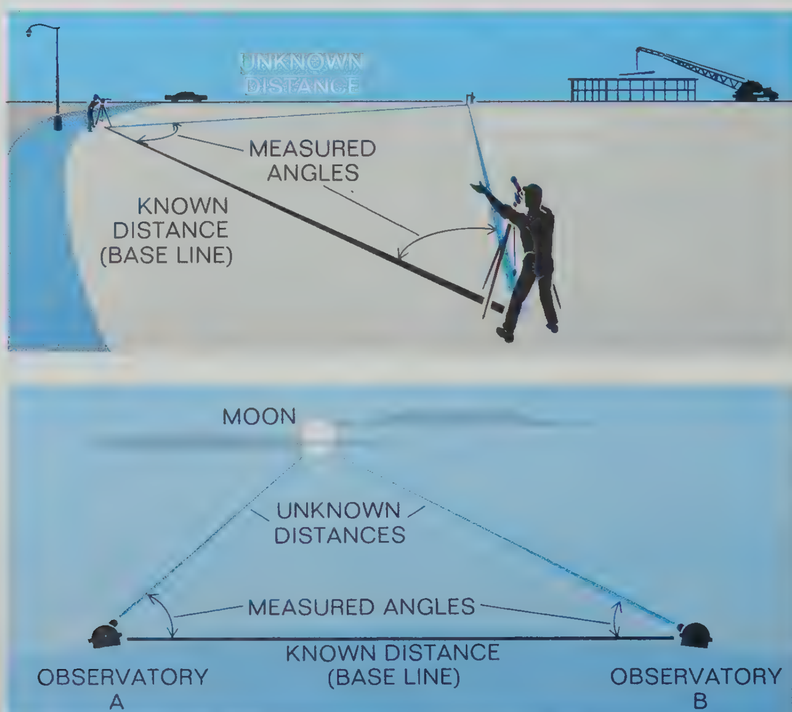


Figure 33-3 *(Upper)* Surveyors measure distances by triangulation, which involves knowing the length of one side of a triangle and measuring two of the three angles. *(Lower)* Astronomers measure the distance to nearby members of the solar system by triangulation. They use the distance between two observatories as the baseline.

348,403 kilometers (238,857 miles) away. Because the moon follows an elliptical path around the earth, its distance from the earth varies by about 30,000 miles. The scientists who plan moon shots must take this into consideration when they calculate the orbit of a moon probe.

Calculating the velocity of the moon in its path is not difficult. It involves analyzing the ellipse of the moon's orbit and then measuring its angular velocity along that path. When this is done, it appears that the moon, on the average, travels about 3,660 kilometers (2,287 miles) per hour.

Figure 33-4 Spring tides and neap tides are direct results of the gravitational forces of both the sun and the moon. When the sun and the moon are in line, spring tides occur. Neap tides occur when the sun and the moon are at right angles to each other.

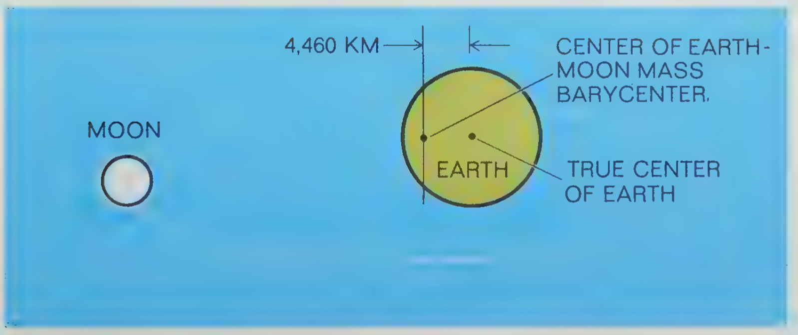
33-3 WHAT CAUSES THE TIDES?

The tide-raising force is an interaction between the gravitational pull of the earth, the sun, and the moon on the water of the oceans. Look at Figure 33-4. It represents a cross section of the earth, with the depth of the oceans very greatly exaggerated. The gravitational force of the earth holds the water tightly to its surface.

If the earth were not rotating on its axis, the oceans would simply bulge up a little directly under the moon because of lunar gravity. The water there would be in a state of balance between the earth's gravitational force, pulling it toward the center of the earth, and the moon's force, pulling it toward the moon. However, the earth does rotate on its axis and around the **barycenter**, which is the center of gravity of the earth and the moon as a system (see Figure 33-5). This complicates matters. It gives a varying velocity and direction of tidal motion to the water of the oceans.

The tidal movement of water is the result of four forces. The strongest force is the earth's own gravity. The second

Figure 33-5 The barycenter is the rotational center, or the center of mass, around which the earth and the moon both orbit.



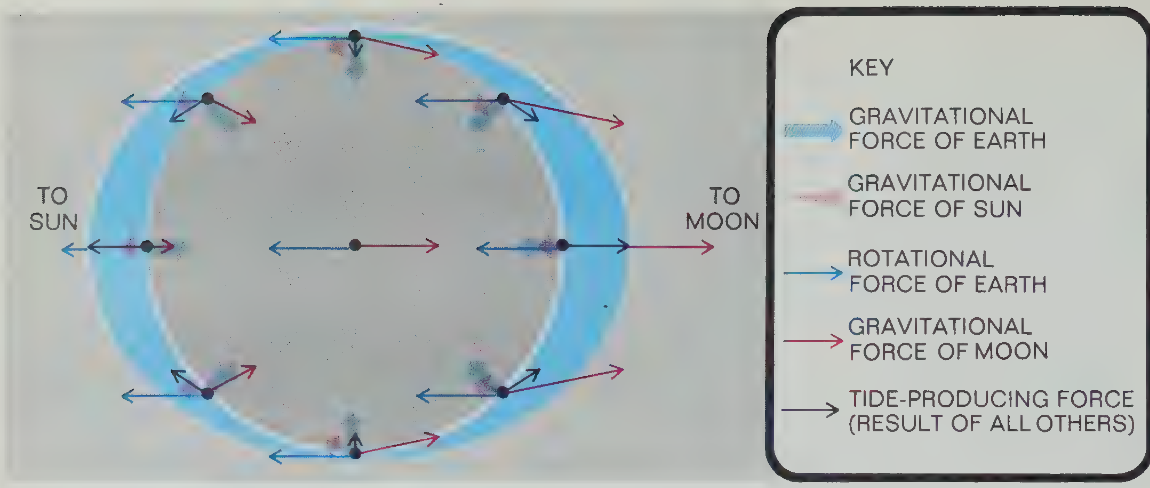


Figure 33-6 The gravitational forces of the moon and the sun and the rotational and gravitational forces of the earth produce tides.

The greatest velocity given to water by the rotational force is about 4.5 kilometers per second. This occurs on the side of the earth opposite the moon. To escape from the earth's gravity, the particles must have a velocity of more than 11 kilometers per second. This is called escape velocity.

force is the rotational force of the earth, which tends to throw water away from the earth. The water does not fly out into space, because the earth's gravity is much greater than the rotational force.

The third force is the gravitational force of the moon on the earth's water. This diminishes with distance, as does any gravitational force. It is greatest on the side of the earth facing the moon. The fourth force is the gravitational force of the sun. This force acts similarly to that of the moon but is only about half as strong. Although the sun is much larger in mass than the moon (27×10^6 times), it is also much more distant (390 times farther away). These four forces are diagramed in Figure 33-6.

It is easy to see why the moon raises the water on the surface of the oceans directly beneath itself. It is not so easy to see why there is also a high tide on the opposite side of the earth. There, the effect of lunar gravity is less than on the side closer to the moon. However, the rotational effect around the barycenter is strongest on the side of the earth opposite the moon. That force raises the surface of the water there into a high tide. Thus, the tides are a complicated response of the water in the oceans to the varying effectiveness of the gravitational forces that operate near the earth (see Figure 33-7).

33-4 WHAT IS THE MOON LIKE?

When you look at a full moon on a clear night, you can see definite patterns of light and dark areas. When the moon is

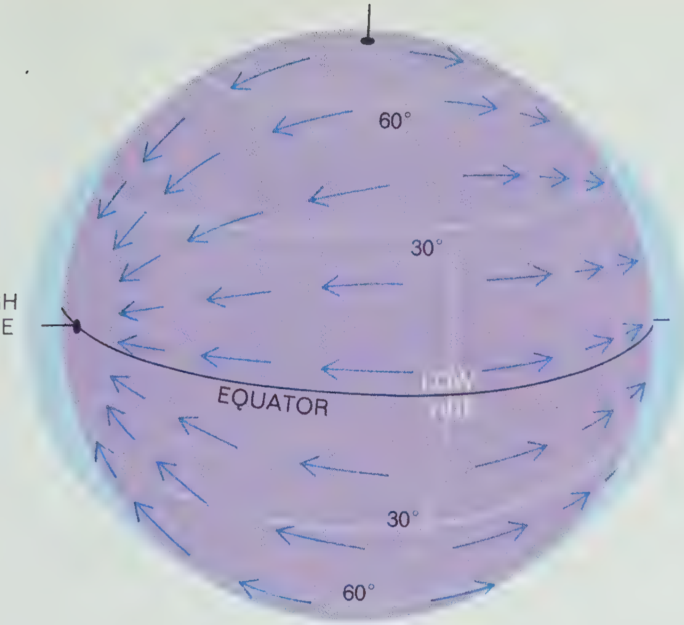


Figure 33-7 High tides appear on the side of the earth directly opposite the moon as well as on the side facing the moon.

studied through a telescope, the surface is seen to consist of smooth and rough areas and of huge, more or less circular depressions. These depressions are usually rimmed with jagged mountains, which cast their shadows on the lunar surface. The smooth areas of the moon are called **maria**, the Latin word for seas. Early astronomers saw them as dark areas and thought they were water. The rough areas are mountains. The great circular depressions are craters (see Figure 33-8).

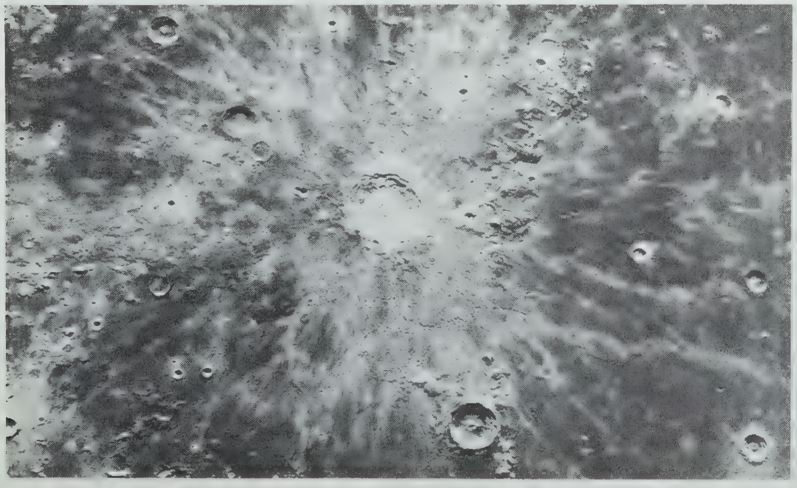


Figure 33-8 The crater Copernicus is probably the most famous crater on the moon. The rays of material surrounding it may be ejecta from the collision with a meteor.

The huge craters on the moon also suggest small meteors with very high velocity.

The origin of these craters has caused a great deal of argument. The most prominent craters are enormous as compared with any on the earth.

Scientists believe that most lunar craters are the results of collisions with meteors. Most moon craters seem to be surrounded by an ejecta blanket like those that surround meteor craters on the earth.

Some lunar craters may be volcanic. Over the past thirty years, astronomers have occasionally noticed dull-red areas in some craters in the shadowed parts of the moon. These may be evidence of volcanism, but they are not at all sure. Probably they will not know the real reason for the red spots or the cause of the lunar craters until an astronaut studies them.

Long before lunar probes televised photographs of the surface of the moon, scientists had wondered what it was like. In 1964 the New York Academy of Science held a conference on lunar geology. The scientists attending the meeting came to the conclusion that the lunar surface is best simulated by very bubbly basalt and by the dust produced by the breakup of that kind of rock (see Figure 33-9). The fact that the density

Figure 33-9 Astronauts testing equipment on a simulated moon surface

Figure 33-10 An atmosphere surrounding a planet or satellite scatters light from a distant star and dims it. As the moon eclipses a star, the star's image is not dimmed. Therefore we believe the moon has no effective atmosphere.

of the moon is 3.33 also supports the hypothesis that the moon may be made of something like basalt. However, we will not know for sure until actual pieces of the moon are collected and studied.

33-5 WHY IS THERE NO AIR OR WATER ON THE MOON?

Astronomers have long known that the moon has neither an atmosphere nor surface water. The reasons for their conclusions are obvious. The moon has no clouds, therefore no surface water. Also, images of stars seen through telescopes do not dim just before the moon passes in front of them. An atmosphere on the moon with a density 1/10,000 that of the earth's atmosphere would cause the image of such stars to dim (see Figure 33-10).

Why does the moon not hold an atmosphere? Gravity on the moon is so weak that the escape velocity is only 2.35 kilometers per second. This is about one fifth as strong as the earth's escape velocity (11.88 kilometers per second). Physicists have measured the velocities of gas molecules and found that they vary with their energy and mass. They have also discovered that even at the same temperature, some molecules move faster or slower than their average velocity.

Sir James Jeans, a famous British astronomer-physicist, discovered that gases traveling slower than escape velocity do escape from a gravitational field. Table 33-1 shows the time necessary for 50 percent of a particular gas to escape from the moon's gravitational field. This table is based on Jeans' calculations.

Table 33-1 Escape rates for various gases on the moon

Gas	*Time for 50% of gas to escape*
Hydrogen	A few weeks
Helium	A few weeks
Water	Several thousand years
Oxygen	Several hundred thousand years
Nitrogen	Several hundred thousand years

The age of the moon is measured in billions of years; therefore, we are sure that any gases that may have existed there have long since escaped into space.

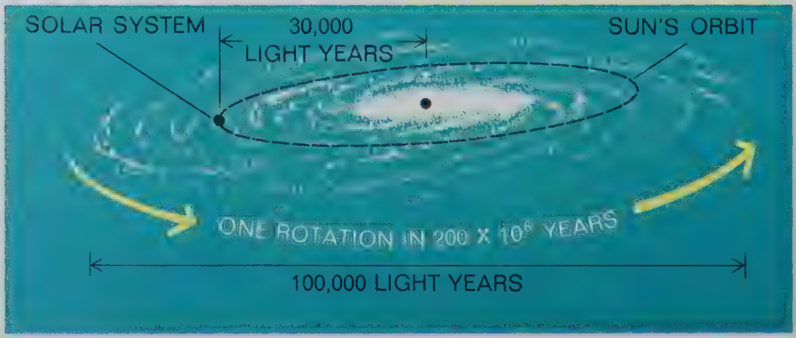
Study Guide

1. What is the difference between a new moon and a full moon? How many days apart are they?
2. How does one compute the distance to the moon?
3. What is the distance to the moon and why does the distance vary?
4. What is the barycenter for the earth-moon system?
5. How does the rotation of the earth affect the tides?
6. Explain why there is a high tide on the side of the earth opposite the moon.
7. What causes the patterns of light and dark areas on the moon?
8. Why is there no air or water on the moon?
9. What kind of rock may be on the moon?

33-6 THE SUN

The sun is the center of the group of celestial bodies that includes the earth-moon pair. This group is called the **solar system.** The only body in the solar system that emits its own light is the sun. Our sun is a medium-sized star in the Milky Way Galaxy. It is believed to be in the outer part of one of the Milky Way's spiral arms. The sun orbits around the galaxy at a speed of about 250 kilometers (155 miles) per second. Even at this tremendous speed, it takes about 200×10^6 years to make a complete orbit around the galaxy (see Figure 33-11).

Figure 33-11 The sun is positioned about halfway out from the center of the Milky Way Galaxy.



You know that all the energy received by the earth comes from the sun. Light travels at 300,000 kilometers (186,000 miles) per second, but the sun is so far away that it takes almost 8 minutes for its light to reach us. The source of the sun's output of energy is a reaction very much like the one that causes a hydrogen bomb explosion. In the reaction, atoms of hydrogen, heated to tremendous temperatures, are converted to helium. The atom of helium produced has less mass than the four hydrogen atoms that were converted. According to Einstein's equation, this mass is converted to huge amounts of energy.

33-7 THE SUN'S STATISTICS

Astronomers, using methods similar to those used to "measure" the moon, have deduced many facts about our sun. Table 33-2 summarizes some of the information we have.

Table 33-2 Statistics of the sun

Distance from Earth (average)	149.5 million kilometers (93 million miles)
Apparent diameter	1.39 million kilometers (860,000 miles)
Mass	329,390 times that of Earth
Density	1.42 grams/cubic centimeter (.25 that of Earth)
Temperature (at surface)	6,000°C (11,000°F)
Temperature (at center)	15×10^6°C (20×10^6°F)

33-8 WHAT DOES THE SUN LOOK LIKE?

By using special telescopes and spectroscopes, we can study the visible surface of the sun. Don't ever look directly into the sun. Focusing your eyes on the concentrated rays can cause permanent damage to your vision.

The sun appears to be composed of at least two parts: an extensive but very low-density atmosphere, and visible

through it we can see a much denser photosphere. The **photosphere** is the luminous surface of the sun we see from the earth. Whether this is the true surface or covers another one beneath we cannot tell. The best hypothesis is that the body of the sun and the photosphere are continuous and that the photosphere is the real surface.

Most of the light from the sun comes directly from the photosphere. At times, dark-looking holes appear on the photosphere. Sometimes these are thousands of miles across, and they are constantly changing shape and disappearing. These **sunspots** appear dark only in comparison with the much brighter photosphere. We believe the sunspots are much cooler areas than the rest of the photosphere. This accounts for their darkness (see Figure 33-12). Sunspots act as "windows" that allow us to see into the sun's interior. Because of the behavior of sun spots, we are almost certain that the sun is all gaseous.

33-9 THE EFFECT OF THE SUNSPOTS

Through the openings that we see as sunspots, the interior of the sun pours various types of charged particles into the surrounding sky. When a large sunspot is directed toward the

Figure 33-12 The dark area in this closeup photograph of the sun is a sunspot. What are thought to be the result of lines of magnetic force can be seen along part of the rim of the sunspot.

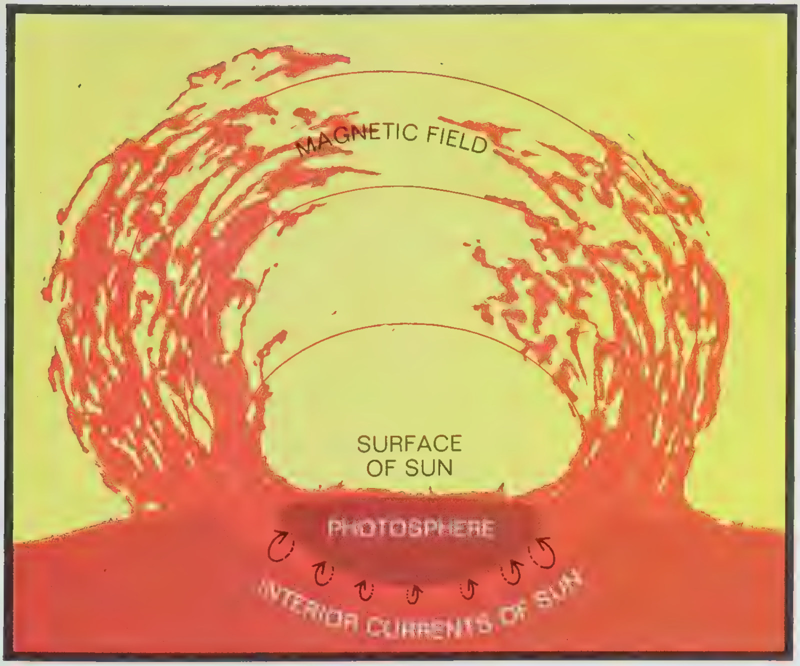


Figure 33-13 Electrically charged particles emitted from sunspots disturb the earth's magnetic field and ionosphere.

earth, this rushing cloud of charged particles disturbs our magnetic field and ionosphere (see Figure 33-13). These charges cause radio waves to behave strangely and therefore interfere with communications. The beautiful *aurora borealis*, the "northern lights," are caused by charged particles from the sun affecting our upper atmosphere (see Figure 33-14).

By following the paths of sunspots across the sun, scientists have been able to time the rotation of the sun on its axis (see

Figure 33-14 When atoms of gas in the ionosphere are excited by solar radiation, we see in the northern skies the *aurora borealis*, or "northern lights." These displays seem to coincide with the periods of great sunspot activity.

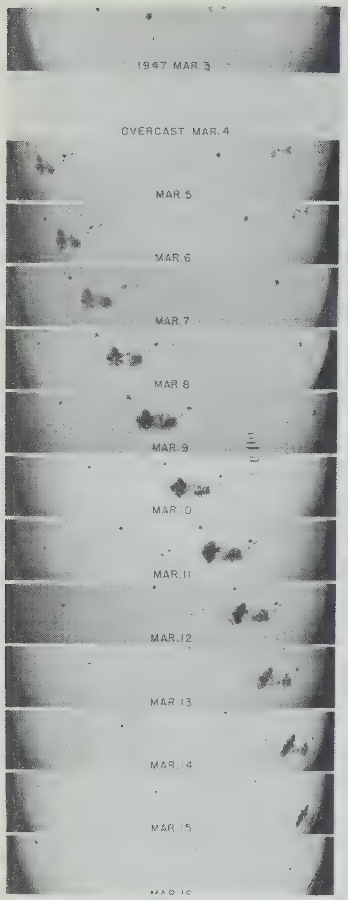


Figure 33-15 By following a series of sunspots across the surface of the sun, astronomers have learned that the whole sun does not rotate at the same angular velocity.

Figure 33-15). We know that every point on the surface of the earth rotates at an angular velocity of 15 degrees per hour (see Section 12-12). Unlike the surface of the earth, the visible surface of the sun does not rotate at a uniform speed. Sunspots at the equator of the sun take 24.65 Earth days to make a full rotation and to reappear at the same spot on the sun's surface. North and south of the solar equator, the rotation of the sun is slower (see Table 33-3).

Table 33-3 Variation in the sun's rotation with latitude

Latitude	*Rotation period in Earth days*
0° (equator)	24.65
15°	25.41
30°	25.85
45°	28.54
60°	30.93
75°	33.15
90°	about 34

Sunspots have been studied by astronomers since Galileo observed them with his crude telescope in 1610. We know they had been seen much earlier by Chinese astronomers, but we are not sure how they saw them. One thing early astronomers discovered was that the number of sunspots that appear and disappear each year varies. In 1843 it was noticed that these numbers fall into a pattern. The maximum number of sunspots appears about every 11.1 years. This is an average length of time; sometimes the **maxima** come only about 7 years apart and sometimes more than 17 years apart. During these maxima, hundreds of sunspots may be visible at any one time, and the sun's surface is never clear. During **minima**, weeks or months may pass without a single sunspot being seen.

It may be unsafe for a manned moon shot during the maxima.

Why should we take any interest in these blemishes on the face of the sun? We have already mentioned that sunspots affect communications on the earth. There is often an increase in the number of magnetic storms on the earth during

sunspot maxima. On the average, these storms occur 25 hours after the responsible sunspot has been directly in line with the earth. Thus, by studying sunspots each day, we can be warned when communications may be disturbed by magnetic storms.

There appears to be a connection between sunspots and meteorology. Andrew Douglass, an astronomer stationed in Arizona, found that variation in the width of the annual rings added to the trunks of growing trees appears to be related to sunspot activity. Other studies have shown that the more frequent sunspots are, the lower is the average temperature. It seems that a difference of about 100 sunspots over a period of a year causes a difference of between 0.5 to 1.0C° in the mean annual temperature.

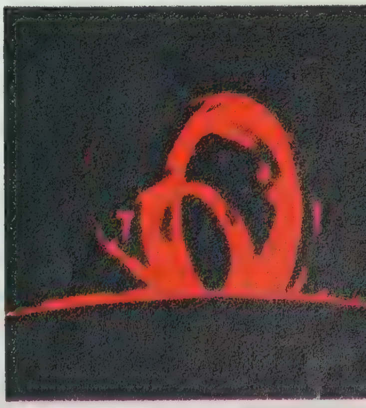
33-10 THE SUN'S ATMOSPHERE

The sun's atmosphere is a thin gas extending thousands of miles above the photosphere. It is composed of the gaseous form of many of the elements found here on earth. Even such elements as iron are there in vapor form. The presence of these elements was discovered by attaching a spectroscope to a telescope and analyzing the spectrum of light coming from the sun. Each chemical element absorbs certain wavelengths (colors) of visible light, leaving a dark line. When the dark lines in the spectrum of the sun are studied, we learn which elements are present as vapor in the sun's atmosphere.

By far the most abundant solar elements are hydrogen and helium. This is what was expected because of the way the sun produces its energy. The hydrogen that was probably once the only element in the sun is slowly being changed to helium and then to the heavier elements. Helium was discovered in the spectrum of the sun before it was found to exist here on the earth. Its name is derived from *helios*, the Greek name for the sun.

Above the denser parts of the sun's atmosphere, there extends a much thinner area composed almost entirely of hydrogen and helium. This is called the **chromosphere**, and is several thousand miles thick. Periodically, great spurts of glowing gases extend outward from the chromosphere, sometimes hundreds of thousands of miles into space. These are called **solar prominences** (see Figure 33-16).

Figure 33-16 Tongues of hot gas surging up into the sun's atmosphere are called solar prominences. This particular prominence rose to a height of 132,000 miles above the sun.



During total eclipses of the sun by the moon, we can see still more of the sun's atmosphere. This is the part called the **corona**. The corona is a very thin gas extending millions of

Figure 33-17 This photograph of the corona was taken during the total eclipse of November 12, 1966, at Pulacayo, Bolivia.

miles into space. Because it is so thin, we cannot see it under ordinary conditions. We look through it to the photosphere.

The corona can be seen for a few seconds during a solar eclipse (see Figure 33-17). When the sun's disk is completely in the shadow of the moon, the light of the corona becomes strong enough to be seen. A total eclipse of the sun occurs, on the average, only about once every 360 years at any one observatory. Astronomers were forced to transport tons of equipment to wherever an eclipse was going to be seen if they wanted to study the corona.

A device called a coronascope was invented by Walter Orr Roberts of the High Altitude Solar Observatory at Climax, Colorado. This is a disk that is placed in a telescope and is just the right size to block out the sun's image. It acts like an eclipse, allowing the observer to view the corona for as long as he wants.

Study Guide

1. What may be happening to the hydrogen and helium in the sun?
2. What are sunspots?
3. How often do the maximum number of sunspots occur?
4. What layer composes the visible portion of the sun? the invisible portion?
5. How does the sun's rotation differ from the earth's?
6. How do scientists determine what elements are found on the sun?

SUMMARY

The moon and the sun are the two members of the solar system that have the greatest influence on the earth. By observing the moon from the earth and by studying the results of recent space probes, we have learned much about the moon. It is probably com-

posed of basalt, and its surface is marked with craters, mountains, and flat areas called maria. We know the moon has no air or water because of its weak gravitational attraction.

Despite its small size, the moon has a greater gravitational effect on the earth than the sun has. The moon's and the sun's gravitational attraction on the earth cause the high and low tides. The rotational force of the earth causes a high tide on the side of the earth away from the moon. The moon seems to orbit a point partway between the center and the surface of the earth.

The sun sends out enormous amounts of energy from its deeper layers, where the conversion from matter to energy takes place. Dark sunspots appear on the sun's surface. These affect the earth's magnetic fields, especially when sunspot activity is high. The outer atmosphere of the sun sometimes sends huge billows of flaming gas deep into space. These also affect the earth's communications and weather. Many of the elements found on the earth are also found in the atmosphere of the sun.

REVIEW AND DISCUSSION QUESTIONS

1. The earth will appear to have phases to astronauts who land on the moon. Using diagrams similar to those in Figure 33-1, explain why this is so.
2. Astronauts landing on the moon will have to protect themselves from the dangerous high-energy solar radiation they will be exposed to. Why do we not have this problem here on the earth?
3. What is the cause of a solar eclipse? Why is it that a full solar eclipse (the covering over of the whole face of the sun) can only be seen in a small part of the world at any one time?
4. The sun transforms hydrogen to helium at a rate of about 4.24×10^{12} grams (about 4 million tons) per second. The total mass of the sun is about 1.98×10^{33} grams. Assume that when all the hydrogen is converted to helium, the sun will "burn out." How much longer will this take? (3.16×10^{7} sec = 1 year)
5. How can we make sure that a dark spot on the sun is a sunspot and not the image of a planet crossing the face of the sun?
6. How can you explain the evidence that the various latitudes on the face of the sun rotate at different speeds?
7. Why is the presence of large amounts of helium in the spectrum of a star considered to be a sign of old age?
8. Why do sunspots appear black against the sun's surface? Is this the reason that the maria appear dark on the moon's surface?
9. Why are the mountains on the moon much more rugged than even the youngest ones on the earth? What is the importance of the fact that there never seems to be a change in the appearance of any of the moon's craters?

CHAPTER 34

SPACE

The bodies that make up the solar system are far nearer to each other than to any other celestial bodies. Planets, planetoids, meteors, and comets have two characteristics in common. They all circle the central sun and follow paths that can be predicted. This is why we call the solar system a system.

34-1 OUR COMPANIONS IN SPACE

You have already learned that each member of the solar system circles the sun in an elliptical orbit. Also, you know that all the members follow Kepler's second law of planetary motion. Kepler discovered a third law about the solar system. He found by mathematical calculation that the time a planet takes to make one revolution around the sun (its period) is related to the average distance of the planet from the sun. This discovery enabled astronomers to calculate the distances of the various planets from the sun, since their period could be learned by observation. A year is a different length of time for each of the planets. Astronomers have also learned that the length of a day is different for each planet.

Just as scientists were able to determine the density of the moon, they were also able to calculate the density of most of the planets. When this was done, astronomers noted a curious fact. The planets can be divided into two groups, mostly on the basis of their density. Mercury, Venus, Earth, Mars, and the planetoids are all small, dense bodies. They are called the inner, or minor, planets. Jupiter, Saturn, Neptune, and Uranus are large, low-density planets. They are called the outer, or major, planets. The most distant planet, Pluto, is included in the outer group, although it may be smaller than Earth.

Some characteristics and details of structure of only three planets besides Earth are well known. These planets—Venus, Mars, and Jupiter—are the ones most likely to be explored by space probes and perhaps by man in the near future. For this reason, we shall describe these three planets separately. The basic information we have about all the planets is summarized in Table 34-1.

The largest and most powerful radio-radar telescope in the world is at the Arecibo Ionospheric Observatory in Puerto Rico.

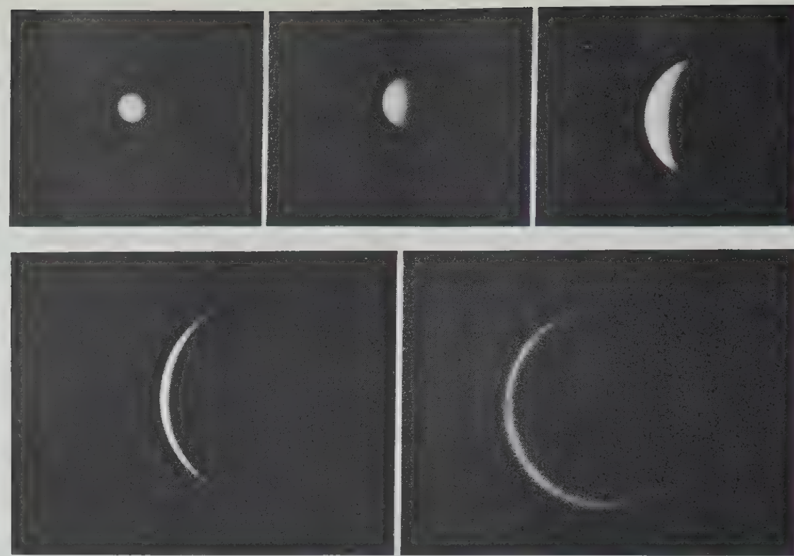


Figure 34-1 The phases of Venus

34-2 THE PLANET VENUS

The orbit of the planet Venus lies between the orbits of Mercury and Earth. It is by far the brightest and most conspicuous planet in the sky. Venus has acquired the names "morning star" and "evening star" because it is best seen a few hours before sunrise or after sunset. With a small telescope, and sometimes even with a good pair of field glasses, you can see that Venus shows phases very much like those of the moon (see Figure 34-1). When Venus is between Earth and the sun, it appears large and crescent-shaped. When it is on the far side of the sun from Earth, it appears small and disk-like (see Figure 34-2).

Of all the planets, only Earth appears to be denser than Venus. Venus is much like Earth in gravity and size and density (see Table 34-1).

Since 1962, both the Soviet Union and the United States have launched space probes to study Venus. The 1967 Soviet

Figure 34-2 The orbit of Venus as seen from the earth. A series of phases much like those of our moon but varying in size becomes apparent when Venus' position in relation to the earth and the sun changes.

Table 34-1 Planets of the solar system

Planet	*Average distance from sun (km)*	*Rotation time*	*Length of year*	*Diameter (km)*	*Average density (g/cm^3)*	*Number of satellites*	*Temperature (C°)*
Mercury	5.7×10^7	59 days	88.0 days	4,800	4.8	0	>400
Venus	10.7×10^7	249 days	224.7 days	12,160	4.9	0	>400
Earth	14.8×10^7	23.9 hrs.	365.3 days	12,756	5.52	1	−40 to 40
Mars	22.7×10^7	24.6 hrs.	687.0 days	6,720	3.95	2	−100 to 23
Jupiter	77.7×10^7	9.8 hrs.	11.9 yrs.	142,400	1.34	12	−160 to −120
Saturn	1.4×10^9	10.2 hrs.	29.5 yrs.	118,000	0.69	9	−140
Uranus	2.9×10^9	10.8 hrs.	84.0 yrs.	48,000	1.36	5	−160
Neptune	4.5×10^9	15 hrs.	164.8 yrs.	44,800	1.30	2	−160
Pluto	5.9×10^9	6.4 days	248.4 yrs.	5,760	?	0	−170

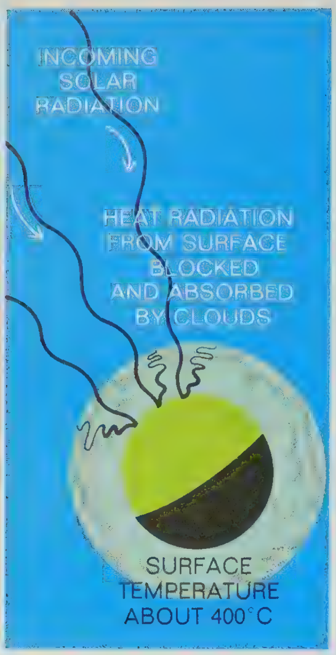


Figure 34-3 As you have learned, our air temperature is largely the result of short-wavelength solar energy being changed to long-wavelength heat energy at the earth's surface. On Venus the heat is held in the atmosphere by carbon dioxide.

probe Venera IV parachuted a small package of instruments to the Venusian surface. The American probes measured Venus as they passed near the planet. The Soviet and American space probes made similar measurements of the atmosphere and surface of the planet.

The Venusian atmosphere appears to be almost 100 percent carbon dioxide. The temperature at the surface was measured at more than 400°C (about 800°F)—much too hot to support any form of Earthlike life. The high temperature on Venus is probably the result of a "greenhouse effect," assuming that our guess about the carbon dioxide atmosphere is correct (see Figure 34-3). Carbon dioxide gas allows the short-wavelength energy from the sun to penetrate to the surface but does not let the long-wavelength heat energy escape back into space.

The space probes found no magnetic field surrounding Venus. The magnetic belt surrounding Earth helps stop some of the sun's damaging high-energy radiation from penetrating our atmosphere. If such radiation did reach the surface of Venus, it would destroy any unprotected forms of Earthlike life that might exist there.

Until recently, the length of a Venusian day was not known. Astronomers had been unable to discover the rotation rate of Venus by observing the planet through telescopes. The surface of Venus that reflects light to us is not the true surface of the planet. We know that the visible part of Venus is a solid blanket of clouds far above the true surface. These clouds probably are composed of frozen crystals of carbon dioxide. Thus, we are not able to see landmarks as Venus turns on its axis.

Recently, however, scientists have bounced radar signals off the surface of Venus. By measuring the changes in the signals as they returned, scientists learned that Venus rotates once on its axis every 249 Earth days. This means that one Venus day is 249 Earth days long. An even more surprising discovery was made. Venus turns on its axis in a direction opposite that of all the other planets.

Study Guide

1. What do the four planets nearest the sun have in common?
2. How can we compare Venus and the moon as seen from Earth?
3. What probably makes up the Venusian atmosphere?
4. How does Venus differ from the other planets in regard to its rotation?

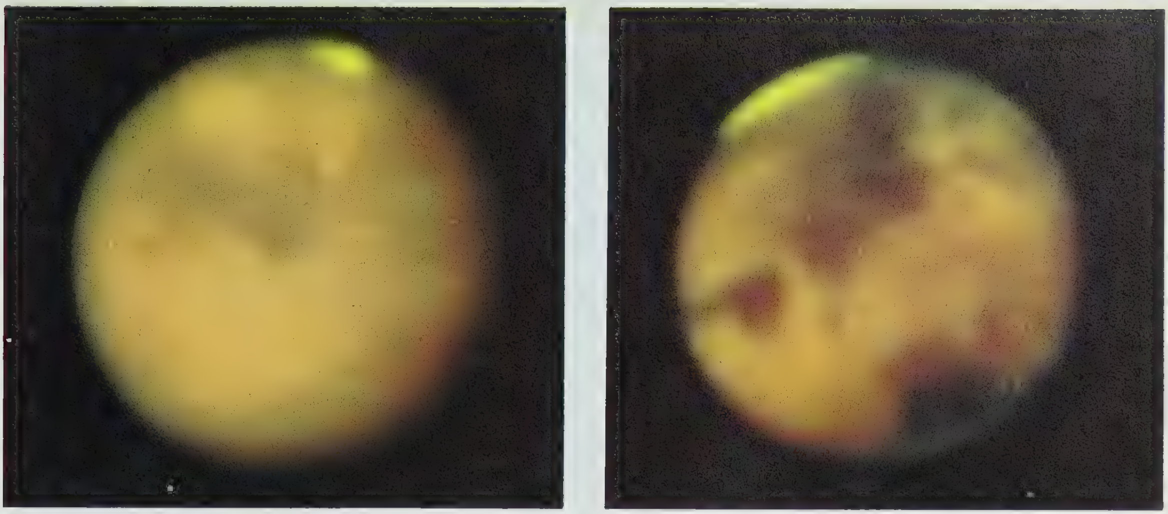


Figure 34-4 The polar caps of Mars appear to grow and shrink, depending on the time of the year they are observed. Scientists think this might be an indication that Mars has seasons.

34-3 THE PLANET MARS

Perhaps even more than Venus, Mars has stirred the imagination of fiction writers. In 1877 the astronomer Giovanni Schiaparelli believed he had discovered a network of straight, dark lines on the Martian surface. He called them *canali* (Italian for canals). Today, even with space probes and superb telescopes, we are not sure of the true significance of the markings on Mars. The idea that the canals on Mars, if they exist, were constructed by some form of intelligent life is mostly due to the imagination of fiction writers.

One fact about Mars has been well established. This is the expansion and contraction of light-colored areas in the polar regions (see Figure 34-4). When the light area is largest at the Martian north pole, it is smallest at its south pole, and vice versa. This is the kind of observation an astronomer on Mars could make about Earth. At the Martian poles there may be accumulations of ice that change with the seasons.

At any time of year, a good telescope shows that the surface is mottled with light and dark areas. Perhaps these are the markings that were once thought to be canals. The light areas have a yellowish-red tone. The dark ones vary from bluish-green to chocolate-brown. These dark areas seem to become larger and greener in the hemisphere where the Martian spring is occurring. It has been suggested that these changes are due to the growth of some form of plant life. Cameras equipped with special film may help us determine whether these areas are plant life.

Figure 34-5 This closeup photograph of Mars shows details that had never before been seen by astronomers. It was taken by a camera on the Mariner IV space probe.

34-4 THE EXPLORATION OF MARS

At present, we can only explore Mars by telescope and by space probe. The information we have gathered has led to many hypotheses about the Martian atmosphere. First, the gravity on Mars is strong enough for its atmosphere to contain the same gases as ours. Second, studies of the light reflected from Mars and measurements taken by the Mariner IV space probe show that the atmosphere is very thin. The fact that we can see the surface clearly is also strong evidence of a thin atmosphere. Third, Mars rarely has clouds. If you look at Figures 15-9 through 15-13, you will see that clouds are the most prominent feature of Earth as seen from space.

We know that the Martian atmosphere contains very little water vapor and even less oxygen. It is probably about one fourth carbon dioxide. Almost all the rest is probably nitrogen. Less than 1 percent is water vapor, oxygen, and other gases. Therefore, we are sure that the atmosphere could not keep a man alive.

The most recent estimates of the atmosphere on Mars show that air pressure at the Martian surface is about 25 millibars. Compare this with the normal air pressure at sea level on Earth – 1013.2 millibars. A Martian explorer will need a pressure suit in addition to his oxygen supply.

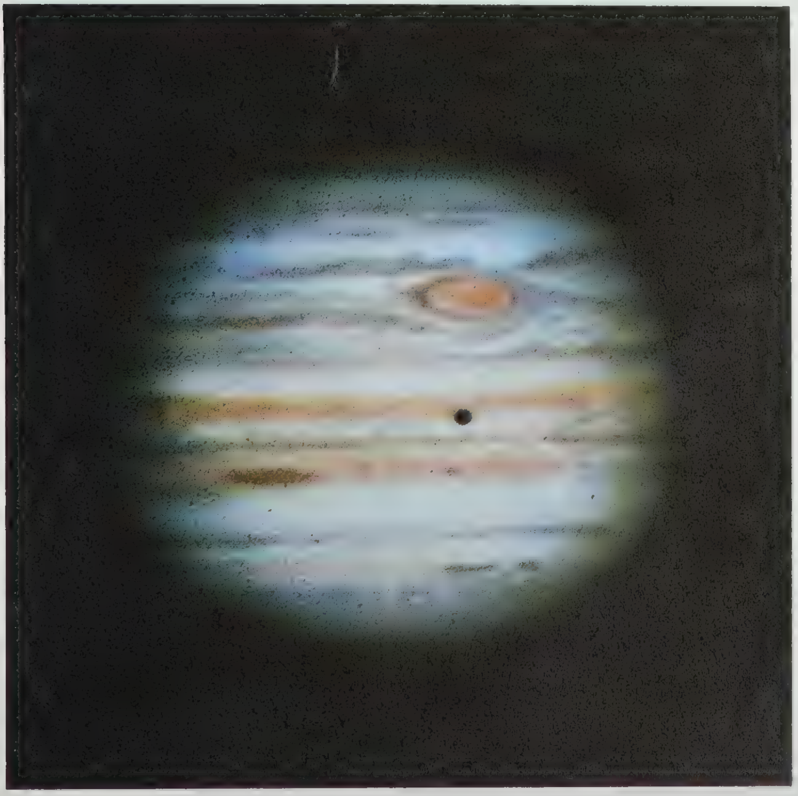
The photographs of the Martian surface televised to Earth from Mariner IV contained a surprise (see Figure 34-5). The surface is marked with craters similar to those on the moon. No one had ever seen craters on Mars from Earth, although

several scientists had predicted their existence. The number of sharply defined craters on Mars is much less than the number on the moon. The explanation is that many of the early Martian craters have been smoothed down by water erosion before Mars lost its water. As the planet's water escaped into space, erosion except by wind diminished and then ceased. Since then, the craters we now see on Mars have accumulated and changed little.

34-5 THE PLANET JUPITER

Jupiter, the giant of the solar system, is one of the brightest objects we can see in the sky (see Figure 34-6). Both the volume and the mass of Jupiter are larger than those of all the other planets combined. In spite of its size, Jupiter's surface

Figure 34-6 Jupiter, the first of the outer or major planets, is the largest planet in the solar system. The Red Spot is one of the distinctive marks on Jupiter. Jupiter's inclination is only 3 degrees.



Moving on Jupiter would be like carrying a load 2.6 times our own weight. A space vehicle taking off from Jupiter would need six times the power it would need on Earth.

It is the kind of atmosphere that biochemists suggest is necessary for the origin of life. If Earth ever had any ammonia in its atmosphere, that gas escaped or was used up billions of years ago.

The four largest moons were used by mariners and explorers as a clock by which Greenwich time could be calculated from anywhere on Earth.

gravity is only about 2.6 times that of Earth. The very low density of the planet (see Table 34-1) suggests that only the lightest elements exist there.

The sunlight reflected to us from Jupiter has passed twice through its atmosphere. The changes in the light caused by the substances of the atmosphere are important in studying a planet. By analyzing the light with a spectroscope, scientists have discovered that Jupiter's atmosphere seems to be composed very largely of hydrogen and helium. Traces (less than 1 percent) of ammonia (NH_3) and methane (CH_4) have been detected. The uppermost clouds may be composed of crystals of frozen ammonia. Lower clouds may be ice crystals. Because of Jupiter's strong gravitational attraction, its original atmosphere may not have escaped.

The density of Jupiter is very low: 1.34 g/cm^3. This is less than the density of water saturated with table salt! Much of Jupiter must be composed of substances quite strange to the lithosphere of Earth. It has been suggested that the most common material (about 78 percent) of the planet is solidified ("metallic") hydrogen at extremely high pressures.

A curious feature of Jupiter, first observed in 1831, is a pinkish area called the Red Spot (see Figure 34-6). This area is about 30,000 by 10,000 miles. The intensity of its color and, to some extent, its shape change slowly. No satisfactory explanation of the Red Spot has been made. One hypothesis is that it is the atmospheric effect of some unusual surface feature.

Jupiter has at least 12 satellites, or "moons." Four of these are almost the size of our moon. The others are much smaller, the smallest being about 100 kilometers (62 miles) in diameter.

34-6 SOME PECULIARITIES OF OTHER PLANETS

We know very little about the other planets except their distances and periods. Saturn, however, is different from any other planet in one respect. It is surrounded by rings (see Figure 34-7). These rings are very thin (only about 16 kilometers deep) but about 53,000 kilometers wide. They are visible only when the axis of Saturn is tilted toward Earth. It is believed the rings are composed of ice crystals and possibly cosmic dust particles.

The most distant planet is Pluto, which is about the size of Earth. Its orbit is somewhat different from the orbits of the other planets. Some astronomers have suggested that Pluto

Figure 34-7 Although Saturn is one of the larger planets, it has the lowest density. The rings of Saturn are one of the spectacular phenomena seen through a telescope.

once was a satellite of Neptune and escaped its orbit. This would explain the curious path it follows around the sun (see Figure 34-8).

34-7 FROM GASES TO SOLAR SYSTEM

In the eighteenth century there were proposed two conflicting theories to explain the formation of the solar system. One of these was suggested by Buffon, who, as you recall, tried to estimate the age of the earth (see Section 8-1). Buffon suggested that a near-collision occurred between the

Figure 34-8 Pluto was the first planet discovered by mathematical calculations. Its eccentric orbit is different from any other planet's orbit in the solar system.

Figure 34-9 The ring nebula in the constellation Lyra

sun and another star. This caused a huge gravitational force between the two, which pulled a great amount of matter from the sun. Most of this material fell back into the sun as the two stars moved apart. The little bit that remained in space gradually gathered into masses that became the planets.

Buffon's theory has two poor features. First, the orbits of planets that were formed according to Buffon's theory would be strongly elliptic. However, we know that the orbits are almost circular. Second, the probability is extraordinarily small that two stars would approach each other close enough to cause material to stream into space.

The second proposal was made by Laplace, a French astronomer-mathematician. Laplace believed the solar system formed from a cloud of celestial gases, called a **nebula** (see Figure 34-9). Gravitational forces within this cloud are believed to have caused the cloud to contract and swirl. The greatest contraction of gases is thought to have occurred in the center of the cloud. This led to the formation of the sun, which contains about 99.9 percent of the matter in the solar system. Outward from the center, several other minor centers of contraction formed in the swirling gases. Each of these formed a planet.

Laplace's theory seems to fit what we know about the solar system better than does Buffon's. This does not mean that Laplace's idea is proved. There are at least three reasons why scientists are unwilling to completely accept Laplace's theory.

The sun rotates on its axis much too slowly for the velocities of the planets in their orbits. More of the cloud should have condensed into planets, possibly as much as one third of it. The great difference in density between the minor planets and the sun and the major planets does not fit the theory. It is safe to say that we do not yet know how the solar system formed.

Study Guide

1. What feature of Mars indicates the occurrence of seasons on the planet?
2. What evidence is there for and against life on Mars?
3. How do the mass and volume of Jupiter compare with those of other planets?
4. What is the most noticeable marking on Jupiter as seen through a telescope?
5. How does the orbit of Pluto differ from those of the other planets?
6. Describe Laplace's theory for the formation of the solar system.

34-8 WHAT LIES BEYOND THE SOLAR SYSTEM?

In Chapter 33 you learned that the sun and its family are a part of a galaxy called the Milky Way. Galaxies are enormous clusters of stars that appear to be in a rotating system. In a galaxy—and there may be hundreds of millions of them in the universe—stars are about 3×10^{13} kilometers apart on the average. Our sun is about 3×10^{17} kilometers from the center of our galaxy.

These numbers are so large that they are almost meaningless to us. Space is so immense that there is little chance of stars or planets colliding.

The space between the galaxies is greater than that between the stars of a galaxy. Groups of galaxies appear to be related to each other. These are called **galaxy clusters**. No one has discovered another universe, but there may be others. This is for future astronomers to debate.

34-9 WHAT FILLS THE SPACE BETWEEN STARS?

Within the solar system, the space between the planets is filled with a thin gas called **interplanetary medium**. We think the air about us is thin but it contains about 3×10^{19} molecules per cubic centimeter. Interplanetary medium contains only from 1 to 10 atoms per cubic centimeter. The source of this medium is the sun. It consists of particles released by the sun. The movement of these particles through interplanetary space is called **solar wind**. It sweeps by our planet and all the others.

Astronomers have discovered a similar thin gas, with about 1 atom per cubic centimeter, around the stars of our galaxy. They have named this substance **interstellar medium.** We believe it is composed of atoms that are escaping from stars and it is like the interplanetary medium produced by our sun. Between the galaxies of a cluster, there may be an even thinner substance, "intergalactic gas." If this gas does exist, it contains less than 1 atom of matter per 10^5 cubic centimeters (less than 10 atoms per cubic meter).

34-10 THE MOVEMENT OF STARS

When we watch the night sky, the pattern of the stars is the same, night after night and year after year. The planets were discovered because, unlike the stars, they do not have a fixed place among the points of light we see in the sky. Using modern instruments, astronomers have discovered that stars also move.

The stars closest to us move enough to allow their movement to be measured photographically. When two photographs taken months or years apart are compared, we find the stars have shifted a little in relation to one another. Our knowledge of the movement of more distant stars is based on a physical effect called the red shift.

34-11 THE RED SHIFT

When you are waiting at a railroad crossing for an approaching train to pass, you hear the train's whistle. As the engine approaches, the pitch of the whistle shifts to a higher note. As the train passes, the pitch of the whistle becomes lower. Why does the pitch of the sound from the whistle shift?

What your ear records are the sound (pressure) waves in the air caused by the whistle. Each pitch of sound is caused by a specific wavelength of sound waves. The number of waves that strike your ear per second determines what pitch you hear. The more waves per second, the higher is the pitch of the sound.

As the train approaches, both the whistle and the sound waves are moving toward you. This causes more sound waves to strike your ear per second than if the train were standing still (see Figure 34-10). When the train passes you and goes away from you, the number of sound waves per second that reach your ear diminishes. In this case, the number is controlled by the velocity of sound *less* the velocity of

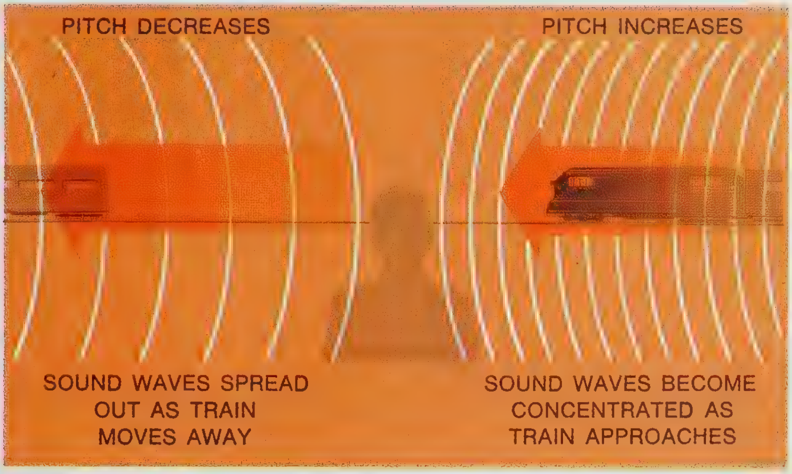


Figure 34-10 The pitch of sound depends on how many sound waves reach your ears per unit of time. In the same way, the color of light depends on how many light waves reach your eyes per unit of time. Moving sources of sound or light produce the Doppler effect.

the retreating train. The effect of a moving source of sound or light was explained by Christian Doppler and is known as the **Doppler effect**.

Now back to the movement of stars. We see stars because they emit light. Light is a form of energy that has wave features. Therefore, any movement of the source of the light relative to you will change the wavelength of light that you see. Scientists study photographs of the spectrum of light from a distant star. Some of the brightest lines that they see are those produced by the hot hydrogen wavelengths of the star (see Figure 34-11). From laboratory experiments we know the wavelength of those lines with great accuracy. By comparing the positions of the hydrogen lines in the star's actual spectrum with their positions in laboratory experiments, we can determine the movement of the star.

If the lines are shifted toward the red end of the spectrum, it means that the light waves of the hydrogen lines have been lengthened. This is what happens if the source of the light

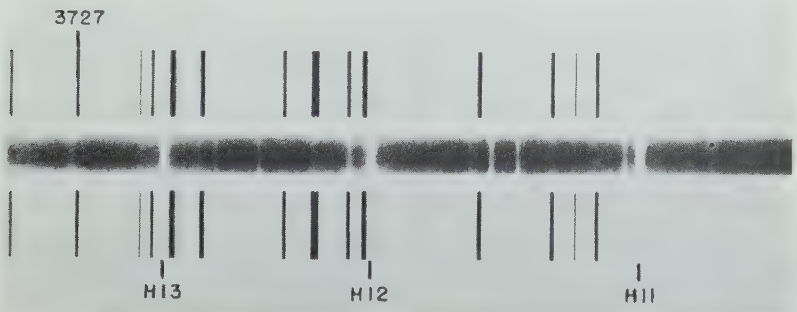


Figure 34-11 The spectrum of Star HD 193182 is the wide, horizontal line crossed by white lines. The star spectrum has been placed between two reference spectra. Note that the hydrogen lines point to white lines in the star spectrum.

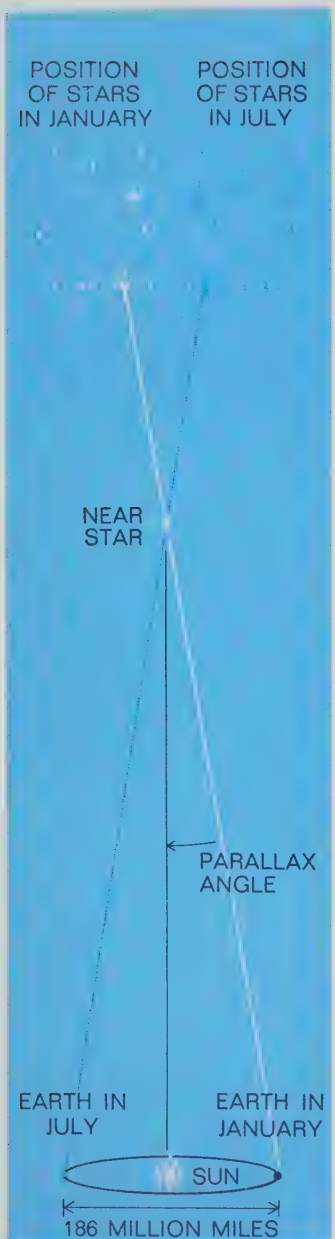


Figure 34-12 You can demonstrate parallax by holding your finger at various distances from your nose and alternately opening and closing each eye. What happens to the relative position of your finger as you move it farther away from your nose?

(the star) is retreating from the earth. If the hydrogen lines are shifted toward the blue end of the spectrum, then the star is advancing toward the earth.

After astronomers had measured the Doppler effect for many stars, they made a startling discovery. They found that all the stars, except some of those in our own Milky Way, are moving away from us. Within the Milky Way, some stars are moving toward us (blue shift) and some away from us (red shift).

34-12 HOW FAR AWAY ARE THE STARS?

The distances to the stars are so great that to state them in miles or kilometers is clumsy. Astronomers invented a measure called **parsec**. A parsec is 3.08×10^{13} kilometers in length. Another, older measure of astronomic distances is the light-year. This is the distance light travels in one year —about 0.946×10^{13} kilometers. A parsec is about 3.26 light-years (see margin on opposite page).

Measurement of the distances to stars had to await the invention of photography and the spectroscope. Today there are several ways to make such measurements. Two of the methods appear to be accurate. The two accurate methods, using trigonometry, are called **parallax methods.** These are similar to the method used by astronomers to measure the distance from the earth to the moon.

The more accurate parallax method can be used only for stars that are near us. Photographs of a star and its background of much more distant stars are taken six months apart. During that time, the earth has traveled halfway around its orbit and is more than 185 million miles from where it was when the first picture was taken. This distance is used as the base of a triangle, with the star at the apex (see Figure 34-12). From the two photographs the astronomers measure the apex angle. They then can solve the triangle for the distance from the star to the earth.

This method can be used for stars not farther away than 20 parsecs. Beyond that, other methods must be used. A rather complicated method that uses photographs of stars taken at least 50 years apart can be used to trigonometrically calculate distances to stars up to 40 parsecs away. Beyond that distance, the methods yield only vague results. The method for measuring distances to distant stars is the red-shift method. This method can be used for indirectly measuring the most distant objects observable by telescope.

34-13 THE EXPANDING UNIVERSE

The astronomers' understanding of the red shift indicates that all stars outside our own galaxy seem to be retreating from us, and from each other. If this is true, the whole universe must be growing (see Figure 34-13). How can we explain an expanding universe?

George Gamow, an American physicist, has suggested that all the matter of the universe was once concentrated in a sphere only about 8 times the size of our sun. The temperatures and pressures that may have existed in such a body would have caused it to explode. This idea is called the **big bang hypothesis.** It seems to explain why we see all the material in the universe spreading apart. When did this super-explosion take place?

The most distant galaxies that we have been able to study are 10^6 parsecs away. From the red shift of their light, they seem to be traveling away from us at the rate of 100 kilometers per second. This velocity, divided into the distance of 10^6 parsecs, suggests that the present universe started expanding at least 10^{10} years ago.

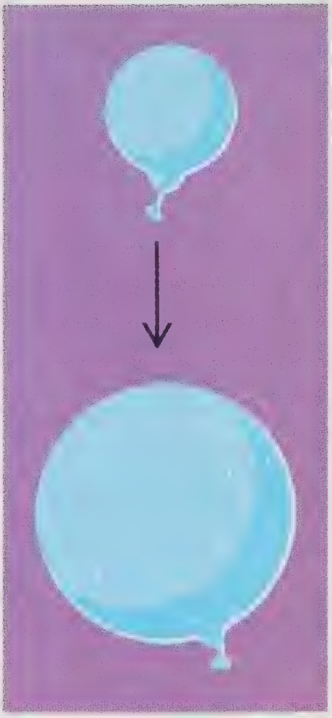


Figure 34-13 Imagine that the dots on the surface of the balloon are galaxies. As the balloon is filled with air, the dots move away from each other.

34-14 IS THE EXPANDING UNIVERSE THE ONLY POSSIBLE KIND?

There are other ways to explain our universe. To be acceptable, any explanation must account for the red shift. The hypothesis least different from the big bang hypothesis is that of the **pulsating universe.** According to this hypothesis, the universe would expand for a period of time and then contract. Such a universe could keep this up infinitely. If our universe is pulsating, then the present stage of expansion has been going on for at least 10^{10} years

Another kind of universe can be imagined in which the galaxies are more or less fixed in space. If our universe is this type, then light must behave very differently from the way we believe it does. The discovery of quasars has produced evidence that some of our ideas about light may be wrong.

The word *parsec* is a contraction of *parallax* and *second.* A parsec is about 1.9×10^{13} miles.

34-15 QUASARS

During World War II, one of the the important new devices used was radar. At times, radio waves produced by sunspots disturbed the use of radar equipment. The late Karl Jansky, of the Bell Telephone Laboratories, turned his attention to this phenomenon. He discovered that not only the sun but

also many parts of the sky emit detectable radio waves. This was the beginning of radio astronomy. To follow up Jansky's discovery, huge radio telescopes, like the one shown at the beginning of this chapter, were built in Australia, Great Britain, and the United States.

As the locations of the sources of the celestial radio "noise" are found, each location is given a number and listed in a catalog at Cambridge University in England. When these sources were first recognized, they were called *quasi-stellar radio sources*, which has been shortened to *quasar*. Almost 500 radio sources in the sky have been located. More than 50 percent of them are associated with distant galaxies. Until recently, scientists were convinced that quasars were invisible. In 1960 the quasar that had been numbered 3C-48 was found to be a dim, starlike object. The name quasar is becoming restricted to this kind of object.

We do not know what a quasar is like. The first quasar to be studied in detail, 3C-48, is a star that emits a variable amount of light. Its spectrum was very puzzling. None of the familiar hydrogen lines that astronomers use for measuring the red shift could be recognized. In 1961 and 1962 several more of these starlike quasars were identified, All had the same qualities that 3C-48 had. In 1963 Maarten Schmidt, of the California Institute of Technology, studied the perplexing spectrum of quasar 3C-273. He discovered the reason the hydrogen lines had not been recognized before. They had been shifted so far toward the red end of the spectrum that they were wholly out of range and almost unrecognizable.

The perplexing thing about quasars is that some of them appear to be retreating from the earth at speeds greater than the speed of light. One of the most important ideas of modern physics is that nothing can travel faster than light. Quasars seem to be doing what we believe cannot be done! Our thinking either about quasars or about light seems to be wrong. Astronomers and physicists are studying the problem. In the future we may be able to explain the curious behavior of quasars.

Study Guide

1. Explain the Doppler effect.
2. What is the movement of stars outside the Milky Way?
3. How are the distances to stars determined?
4. What is Gamow's hypothesis of the formation of the universe?
5. What does *quasar* mean?

6. What impossible conclusion have we reached about the speed of quasars?

SUMMARY

The four planets that are relatively close to the sun are all relatively small and dense. The other planets, except for Pluto, are large and have low densities. Only Mars seems to have an atmosphere and temperature that might support life.

The great mystery of science is the origin of the universe. We know that the universe is composed of several hundred million galaxies. Each galaxy is composed of hundreds of billions of stars. The sun is a small star in a cluster of stars near the edge of the galaxy called the Milky Way.

Astronomers use trigonometry and parallax to estimate the distances of stars and galaxies. From the study of distances we have learned that stars outside our own galaxy are retreating from us. This idea has given rise to the hypothesis of an expanding universe. The discovery of quasars, and especially the discovery that they do not fit well into other facts about the universe, may cause scientists to reexamine what we think is the nature of light.

REVIEW AND DISCUSSION QUESTIONS

1. What did Kepler's third law enable astronomers to do?
2. Explain the use of the Doppler effect in determining the movement of stars.
3. What is the parallax of a celestial body?
4. What is the maximum speed attainable in the universe?
5. Compare how the future of the universe is predicted by two hypotheses of its formation.
6. If Gamow's hypothesis regarding the universe is correct, which galaxy would appear to us to be the oldest and which would appear to be the youngest?
7. Describe the method used in locating radio galaxies.
8. What necessary information must be obtained from space probes to enable man to explore the inner planets?
9. Discuss some of the facts we know about the solar system's structure that make various hypotheses of its origin difficult to explain.
10. Explain the "greenhouse effect" on Venus in relation to possible life forms there.

APPENDIX

APPENDIX I Something About Minerals

At one time or another almost every one of us collects something. Minerals form a very interesting kind of collection. Besides being nice things to collect, minerals are economically important in many industries and are one of the products of the earth that geologists use in their studies. A person who makes a special study of minerals is called a *mineralogist*. There are about 3,000 minerals that have been given names. Of these, there is only a limited number that are helpful in a beginning study of earth science. If you want to know more about minerals, read one of the books from the book list in this appendix.

The recognition of specific minerals is a science that requires considerable training and special equipment. However, there are certain simple clues to the common minerals in which we are interested. Usually there is no one clue that will lead you to the right name for a mineral. Instead, we use combinations of clues. In the following tables we have listed the common minerals that you may come across, together with clues to their recognition. The following mineral properties have been found to be the most useful.

Luster Mineralogists have many special words to describe the great variety of surface appearances of minerals. We need only two of them: *metallic*, which is applied to those minerals that look like pieces of metal, with shiny and opaque surfaces; and *nonmetallic*, which is applied to minerals with all the other surface appearances, such as dull, glassy, pearly, etc. Table A includes the common minerals having a metallic luster, and Table B includes those having a nonmetallic luster.

Hardness Mineralogists use a scale of hardness that was invented by Friedrich Mohs. This is a number scale wherein a mineral with a lower number may be scratched by any other mineral with a higher number. This hardness number used by Mohs is quite different from the real hardness of minerals. We can call it the *scratch hardness* for convenience. Here is the list of Mohs-scratch-hardness minerals with their numbers and a few added items that are useful, with their scratch-hardness numbers.

1 Talc **2** Gypsum **2½** Fingernail **3** Calcite **3½** Copper penny **4** Fluorite **5** Apatite **5½** Knife blade **6** Orthoclase (a feldspar) **7** Quartz **8** Topaz **9** Corundum **10** Diamond.

Very few minerals you will find are as hard as quartz (7). Using your fingernail, a knife blade, a copper penny, and a piece of quartz, you can place the common minerals into the proper divisions in Table A or Table B.

Color Color is not always a particularly useful characteristic. Many minerals vary greatly in color, depending upon impurities that are in them. Nevertheless, color is sometimes a helpful clue, especially among minerals with a metallic luster. When a mineral is scratched on an unglazed porcelain plate, the color left as a streak may be useful. (This is the color of the powdered mineral.)

Crystal system and habit The **system** to which a crystal belongs is based upon the relationships of its axes. However, this does not tell you what the shape of the crystal is. For example, a mineral of the isometric crystal system may be found as cubes, octahedrons, tetrahedrons, or any of a half dozen other geometric shapes. The geometric shape in which a mineral is usually found is its **crystal habit**.

When crystals of a mineral are commonly found, we have noted their general shape in the table. The abbreviation for the word crystal is *xl*. Most of the mineral specimens that you pick up are massive and do not clearly show the geometric system and habit into which they crystallize.

Density Sometimes density is a useful characteristic. Although in theory it is easy to measure the density, large pieces of absolutely pure mineral, free from air pockets, are rather rare. Thus, most density measurements that you make will differ a little from the density given in the tables. Do not let this disturb you. Usually you can decide that a mineral has low or high density by "hefting" it in your hand.

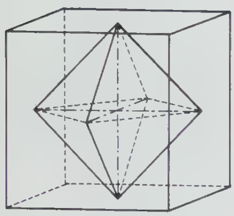
Other clues Here we have listed other clues that mineralogists have found useful in recognizing a particular mineral. One term, used here with the micas, may need to be explained. This is *elastic*. It means that the substance when bent and released will spring back to its original shape. A substance that will bend, but not spring back of its own accord, is said to be *flexible*. *Cleavage* is another term used in describing minerals. It means that the mineral can be split again and again along a given plane.

Using the tables If the mineral has a metallic luster, it will be found in one of the sections of Table A; if the mineral has a nonmetallic luster, it will be found in one of the sections of Table B.

If you can scratch the mineral with your fingernail, you will find the mineral in Section I of the proper table, A or B. If you cannot scratch the mineral with your fingernail but can scratch it with a pocket knife, look for it in Section II of the proper table, A or B. Once you have determined the proper section of the proper table, use the clues that are given under the various headings. It is only a matter of searching to match the clues with your mineral sample.

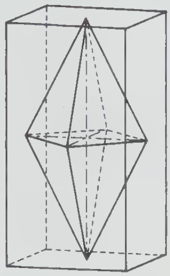
Some minerals are found most commonly as rock-forming minerals. To the number for each of these we have added **R**. The rest of the minerals are usually found in veins or as ores of metals. Some minerals of either class—rock-forming or vein minerals—occur in both situations.

CRYSTAL SYSTEMS



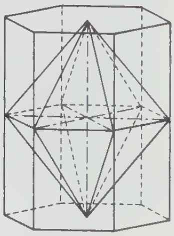
Isometric

The three axes are at right angles to one another and of equal length.



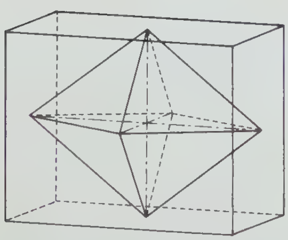
Tetragonal

The three axes are at right angles to one another with two axes of equal length.



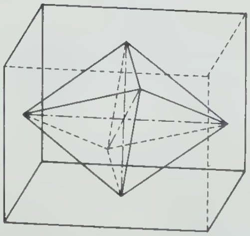
Hexagonal

The three equal-length axes are in a plane and at 60 degrees to each other; the fourth axis is perpendicular to the plane through the point of intersection of the other axes.



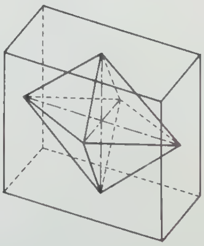
Orthorhombic

The three axes are at right angles to one another and all of unequal lengths.



Monoclinic

Two axes are at right angles to one another and of unequal lengths; the third axis is at an angle to the plane of intersecting axes other than 90 degrees.



Triclinic

No axis meets another at 90 degrees, and usually all axes are of unequal lengths.

Table A Common minerals with metallic luster

No.	Name	Hardness	Color	Crystal system	Density g/cc	Other clues
Section I	*Can be scratched by fingernail (hardness less than 2½)*					
1	Graphite	1	Black	Hexagonal; in plates or massive	2.23	Will make a black line on paper
Section II	*Can be scratched by knife blade but not by fingernail (hardness between 2½ and 5½)*					
2	Galena	$2\frac{1}{2}$	Gray	Isometric; cubic cleavage good	7.6	Cubic cleavage and silvery-gray
3	Bornite	3	Bronze, purple	Isometric; usually massive	5.1	Purple tarnish
4	Chalcocite	3	Gray to black	Orthorhombic; usually massive	5.8	Often has sooty coating
5	Chalcopyrite	4	Brassy	Tetragonal; usually massive	4.3	Often tarnished-blue
6	Pyrolusite	$4\text{-}5\frac{1}{2}$	Gray to black	Tetragonal; usually massive or powdery	5.0 to 5.12	Often earthy, delicate mossy or fernlike thin
Section III	*Cannot be scratched by knife blade (hardness greater than 5½)*					
7	Magnetite	6	Black	Isometric; usually massive	5.2	Magnetic
8	Hematite	6	Red to black	Trigonal; usually massive	5.26	Rusty streak; often earthy and soft
9	Arsenopyrite	6	Silvery	Monoclinic; usually massive	6.1	Commonest arsenic mineral
10	Rutile	$6\frac{1}{2}$	Red-brown	Tetragonal; usually pyramidal xls	4.2	Common accessory mineral
11	Pyrite	$6\frac{1}{2}$	Light brassy	Isometric; xls, or massive	5.0	Common

Table B Common minerals with nonmetallic luster

No.	Name	Hardness	Color	Crystal system and habit	Density g/cc	Other clues
Section I	*Can be scratched by fingernail (hardness less than 2½)*					
12	Talc	1	Pale green	Monoclinic; foliated	2.83	Feels greasy
13R	Gypsum	2	Colorless, white, tinted	Monoclinic; xls, or massive	2.32	Cleaves easily
14R	Chlorite	2	Green	Monoclinic; plates	2.6–3.0	In schists

Table B Common minerals with nonmetallic luster (Continued)

No.	Name	Hardness	Color	Crystal system and habit	Density g/cc	Other clues
Section II	*Can be scratched by knife blade but not by fingernail (hardness between $2^1/_2$ and $5^1/_2$)*					
15R	Serpentine	$2^1/_2$	Green to brown	Monoclinic; massive	2.5–2.6	Alteration of basic igneous rocks
16R	Muscovite	$2^1/_2$-3	Colorless	Monoclinic; thin plates	2.8–2.9	Thin plates are elastic
17R	Biotite (mica)	$2^1/_2$	Black, brown, green	Monoclinic; thin plates	2.9–3.4	Thin plates are elastic
18R	Calcite	3	Colorless, white	Trigonal; xls, massive, rhombehedral cleavage	2.71	Effervesces rapidly with cold dilute HCl
19	Barite	3	Colorless, white, tinted	Othorhombic; tabular xls	4.5	Colors a flame green
20	Goethite	$3^1/_2$-5	Yellow, brown	Othorhombic; massive	4.2	Yellow streak
21	Dolomite	$3^1/_2$-4	White, brownish, pink	Trigonal; massive	2.85	Effervesces slowly with warm dilute HCl; rhombohedral
22	Fluorite	4	Colorless, white, green, purple	Isometric, cubes, massive	3.18	
23	Azurite	4	Blue	Monoclinic; xls, massive	3.77	Effervesces with cold dilute HCl
24	Sphalerite	4	Yellow to black	Isometric; massive	4.0–4.1	Hydrogen sulphide with warm HCl
25	Malachite	4	Green	Monoclinic; massive	4.0	Effervesces with cold dilute HCl
26R	Apatite	5	Brown, green, whitish	Hexagonal; prisms, massive	3.1–3.2	In crystalline rocks
27	Opal	$5^1/_2$	Colorless, white	Massive	2.0–2.2	
Section III	*Cannot be scratched by knife blade (hardness greater than $5^1/_2$)*					
28R	Feldspars	6	White, pink, green	Prismatic xls	2.56	Common in crystalline rocks
29R	Actinolite	6	Green	Monoclinic; fibrous	3.0–3.4	In schists and gneisses
30R	Hornblende	6	Black, green, brown	Monoclinic; long prismatic xls	3.0–3.4	In crystalline rocks
31R	Augite	6	Black, dark green	Monoclinic; short prismatic xls	3.24–3.4	In igneous rocks
32	Hematite	6	Red-brown to black	Trigonal; massive	5.26	Streak rust-red, often earthy and soft
33R	Olivine	$6^1/_2$	Olive-green	Orthorhombic; massive	3.3–3.6	In basic igneous rocks
34R	Rutile	$6^1/_2$	Red-brown to black	Tetragonal; long prismatic xls, massive	4.2–4.3	In crystalline rocks
35R	Quartz	7	Colorless, white, tinted smoky-black	Trigonal; hexagonal xls, massive	2.65	Very common
36R	Garnet	7-$7^1/_2$	Brown, red, green, black	Isometric; xls to massive	3.6–4.3	In crystalline rocks

APPENDIX II The Identification of Rocks

The way to go about recognizing what kind of rock you have in hand is to discover first the answers to these three questions about the rock.

1. Is it sedimentary, igneous, or metamorphic rock?
2. What is the texture of the rock?
3. What are the principal minerals in the rock?

From what you have learned in Chapter 5, you should be able to recognize sedimentary rocks and crystalline rocks. You may have some difficulty deciding whether a particular crystalline rock is igneous or metamorphic. Some of the latter puzzle geologists! In general, metamorphic rocks are streaky and platy (i.e., split easily). If they are neither of these but are granular, they probably are composed almost entirely of one kind of mineral.

All we need are three terms to define igneous texture: *glassy*, which means just that; *fine-grained* (*aphanitic* is the technical term that you may find in some rock books), which means that the individual mineral grains are so small you cannot easily see them without using a lens; *coarse-grained* (granular), which means the individual mineral grains are easily seen and are usually at least 2 or 3 millimeters long. (The term *porphyritic* means "having distinct crystals surrounded by fine-grained material.")

Of the many minerals found in rocks, the most important light-colored ones to be able to recognize are quartz, feldspar, and calcite. The various ferromagnesian minerals are usually brownish or greenish in color, or sometimes so dark that they look almost black.

Table C Sedimentary rocks

Name	Chief minerals	Original sedimentary debris	Notes
Conglomerate	Quartz and pebbles	Gravel	Pebbles vary in size and can be seen to be of other rocks
Breccia (BRECH ee uh)	Rock fragments	Broken rocks	Rock fragments are angular, not rounded
Sandstone	Quartz	Quartz-rich sand	Usually light-colored, often reddish
Arkose	Quartz and feldspar	Feldspar-rich sand	Usually dirty-white to pink
Graywacke	Quartz, feldspar, clay, volcanic ash, slate particles	Sand mixed with clay and tiny rock fragments	Usually dark gray
Shale	Clay minerals	Mud, clay, silt	Particles too small to be seen without a lens
Limestone	Calcite	Shells and calcite mud	Effervesces with cold dilute hydrochloric acid
Dolostone	Dolomite	Limestone or calcite mud that has been altered by seawater	Effervesces only with hot dilute hydrochloric acid
Chert	Opal, chalcedony	Most often silica gel	No grain visible, hard, insoluble
Evaporites	Halite (crude table salt), gypsum	Residues from the ocean or salt lakes	Sometimes salty to taste
Coal, peat	Organic material	Plant fragments	Dark color; burns

Table D The families of igneous rocks

Texture	Most common minerals present			
	Feldspars present			*Feldspars absent*
	Ferromagnesian minerals rare		*Ferromagnesian minerals present*	
	Quartz present	*Quartz absent*		
Loosely cemented fragments	Volcanic tuff (particles small) Volcanic breccia (particles large)			Rare or not known
Glassy	Obsidian (solid) Pumice (frothy)		Basalt glass	Rare or not known
Fine texture (aphanitic)	Rhyolite	Andesite	Basalt	Rare or not known
Granular	Granite	Diorite	Gabbro	Peridotite Pyroxenite Serpentine

Table E The families of metamorphic rocks

Name	Structure	Texture	Chief minerals and derivation
Quartzite	Nonfoliated	Granular	Quartz; derived from sandstones
Marble	Nonfoliated	Granular	Calcite; derived from limestones
Slate	Foliated	Fine	Mica and quartz; splits easily; from shale
Schist	Foliated	Coarse	Mica, quartz, feldspar; splits easily; from fine-textured igneous rocks
Gneiss	Foliated	Coarse	Mica, quartz, feldspar; does not split easily; from igneous rocks, sometimes from schist

Book List on Minerals and Rocks

Berry, L. G., and Brian Mason. *Mineralogy: Concepts, Descriptions, Illustrations.* San Francisco, W. H. Freeman and Co., 1959.

Dana, Edward S., and C. S. Hurlburt. *Minerals and How to Study Them.* New York, John Wiley and Sons, 1949.

Loomis, Frederic B. *Field Book of Common Rocks and Minerals.* New York, Putnam, 1948.

Pearl, Richard M. *How to Know the Minerals and Rocks.* (paperback) New York, New American Library.

Pough, Frederick H. *Field Guide to Rocks and Minerals.* Boston, Houghton Mifflin, 1953.

Zim, Herbert S., and Paul R. Shaffer. *Rocks and Minerals.* (paperback) New York, Simon and Schuster.

APPENDIX III Relative Abundance of Atoms of the Most Common Elements (Silicon is held constant at 1.0×10^4 atoms.)

Element	In universe		In solar atmosphere		In Earth's crust	
Hydrogen	1	4.0×10^8	1	5.1×10^8	4	1.4×10^3
Helium	2	3.1×10^7	2	1.0×10^8	-	Traces
Oxygen	3	2.1×10^5	3	2.8×10^6	1	2.9×10^4
Neon	4	8.6×10^4	-	Traces	-	None (?)
Nitrogen	5	6.6×10^4	5	2.1×10^4	22	3.3×10^0
Carbon	6	3.5×10^4	7	1.0×10^4	13	2.8×10^1
Silicon	7	1.0×10^4	7	1.0×10^4	2	1.0×10^4
Magnesium	8	9.1×10^3	6	1.7×10^4	8	8.8×10^2
Iron	9	6.0×10^3	4	2.7×10^4	7	9.0×10^2
Sulfur	10	3.7×10^3	9	4.3×10^3	15	1.7×10^1
Argon	11	1.5×10^3	-	Traces	-	Traces
Aluminum	12	9.5×10^2	10	1.1×10^3	3	3.0×10^3
Calcium	13	4.9×10^2	12	8.7×10^2	6	9.2×10^2
Sodium	14	4.4×10^2	11	1.0×10^3	5	1.2×10^3
Nickel	15	2.7×10^2	13	4.7×10^2	25	1.4×10^0
Phosphorus	16	1.0×10^2	No data		11	3.8×10^1
Chromium	18	7.8×10^1	14	2.0×10^2	21	3.9×10^0
Manganese	19	6.9×10^1	15	1.5×10^2	14	1.8×10^1
Potassium	20	3.2×10^1	16	8.1×10^1	9	6.7×10^2
Titanium	21	2.4×10^1	18	4.7×10^1	10	9.3×10^1
Fluorine	23	1.6×10^1	No data		12	3.7×10^1

APPENDIX IV The Powers of Ten

Scientists must often deal with either very large or very small numbers. It is difficult to express such numbers in a meaningful way. To make such numbers easier to understand and to compare, scientists use powers of ten. For example, 10^2 is the second power of ten. It is the number we get by multiplying ten by itself, 10×10; that is, 100. Thus, 10^2 equals 100. If you see 10^5, it means $10 \times 10 \times 10 \times 10 \times 10$, which equals 100,000. Notice that the number of zeros (5) is the same as the power (10^5) of ten.

Let us see how scientists use this system. The mean distance from the earth to the sun is 149,500,000 km. The mean distance from Pluto, the outermost planet, to the sun is 5,900,000,000 km. These numbers are more understandable if we write them 1.495×10^8 and 5.90×10^9. From these numbers we can see at a glance that the distance from Pluto to the sun is ten times farther than the distance from the earth to the sun.

For numbers less than 1, scientists use negative powers of ten. Suppose we want to write the length of the radius of a helium atom. This is only 0.000 000 009 3 cm. We could express this as 93/10,000,000,000, or $93/10^{10}$. We can write this in the same form that we used for very large numbers by using a method invented by mathematicians: Division is indicated by placing a minus sign (−) before the power number. Thus, 10^{-10} means one ten-billionth (10^{-10} equals $1/10^{-10}$). Using this convention, 93×10^{-10} equals $93/10^{10}$. Unless there was something important about 10^{-10} cm, a scientist would write 93×10^{-10} as 9.3×10^{-9}. Do you see why these numbers are equal? Usually there is nothing important about 10^{-10} cm, but there is about 10^{-8} cm. This is an accepted unit of measure called the Ångstrom. It is the unit used for measuring the wavelength of light and other very small distances. This fact suggests that the best way of expressing the length of the radius of a helium atom is 0.93×10^{-8} cm.

GLOSSARY

aa. Rough, blocky lava.
absolute humidity. The actual amount of water vapor in a unit volume of air.
abyssal plains. Vast areas of the deep ocean bottom that are almost flat.
adiabatic changes. Changes in temperature with no heat energy being added or lost.
air cell. The circulation pattern developed as air rises, cools, and descends to the earth.
albedo. The amount of incoming solar radiation that is reflected by a surface.
alluvial fan. The fan-shaped mound of alluvium that forms at the base of a mountain where a stream reaches the plain.
alpine folding. Folds in the crust of the earth that lie almost horizontal.
amber. Plant saps that have been buried in sediments and fossilized.
anemometer. An instrument by which the speed of wind is measured.
angular velocity. The rate at which an object traveling in a circular or elliptical path moves along an arc measured by the central angle. The angular velocity of the earth on its axis is 15 degrees per hour.
anticline. An upward fold of the earth's crust, convex to the sky.
anticyclone. A mass of circling air moving outward from a high-pressure area.
arêtes. High ridges left between cirques or glacial troughs.
astronomy. The study of celestial bodies.
atoll. A generally circular reef of coral surrounding a lagoon.
autumnal equinox. September 22, when the sun is directly over the equator and night and day are of equal length.
bar. A ridge of sand built up offshore.
barchan. A crescent-shaped sand dune.
barometer. An instrument used to measure atmospheric pressure.
barrier bar. An offshore sandbar extending above sea level.
barrier reef. The coral formation encircling an island some distance offshore.
barycenter. The center of gravity of the earth and moon as a system.
basalt. A family of igneous rocks associated with lava flows; usually fine-textured and containing iron-magnesium minerals.
bathythermograph. An instrument used for making a continuous record of depth and temperature in the ocean.
batholith. A very extensive mass of solidified magma that originally intruded under a column of sedimentary rocks.
berm. The sandy terrace shoreward of high-tide line on the beach.
block mountains. Mountains formed from raised blocks of the earth's crust.
Bouguer anomaly. The difference between the theoretical and the observed force of gravity.
buoyancy. The force that causes a substance to rise in a fluid.
caldera. A large depression resulting from the collapse of a volcanic peak.
calorie. The amount of heat required to raise the temperature of one gram of water one degree Celsius.
carbon print. A type of fossil resulting from the partial decay of plant material that leaves behind only the carbon of the plant.
cast. A type of fossil resulting from the deposition of minerals within a mold.
Celsius. Temperature scale using 100 degrees for boiling and 0 degrees for freezing of water.
chemical weathering. The breakdown of minerals and rocks by means of chemical reactions.
chert. A kind of rock formed from hardened jellylike silica.
chondrites. Stony meteorites that contain tiny pieces of olivine or pyroxene, or both, embedded in an iron-nickel mass.
chromosphere. The area of the sun's atmosphere composed almost entirely of hydrogen and helium.
chronometer. An instrument used to accurately determine time.
cinder cone. A volcanic cone composed almost entirely of scoria.
cirque. A steep-walled bowl-shaped basin high in the mountains where a glacier originated.
cold front. A mass of cold air advancing into a territory occupied by warm air.
colloidal state. Particles of materials such as clay that have a great affinity for and tend to cling to water molecules.
comet. A celestial body, composed largely of frozen gaseous material, that describes an elongated elipse around the sun.
composite cone. A volcanic cone composed of alternate layers of scoria and lava.
constellation. A group of stars to which a name has been given.
continental shelf. The zone around the continents from the low-water line to the depth at

which there is a marked increase in slope to a greater depth.

continental slope. The outer edge of the continental shelf, with an average pitch of 3 to 4 degrees.

Coriolis effect. The deflection of moving objects to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, brought about by the rotation of the earth.

cP. Continental polar air mass.

convection. Circulation in a fluid due to uneven heating.

corona. A very thin gas extending outward from the sun; it can usually be seen only during a total eclipse of the sun or with special equipment.

crater. A depression or opening found at the top of any volcano.

crevasse. A crack in the upper part of the ice of a glacier.

cross-bedding. Sand layers at abutting angles of deposition in a dune.

crust. The relatively thin outermost layer of the earth.

cuesta. A ridge having a gentle slope facing toward the coastline and a steep slope facing inland.

cutbank. The side of a meandering stream that is being eroded.

cyclone. Any system of winds blowing in toward a low-pressure area.

debris. The broken and weathered bits of rock on the surface of the earth.

delta. An alluvial deposit at the mouth of a stream.

density. The mass in grams of one cubic centimeter of a substance; it equals the mass divided by the volume.

dew point. The temperature of the air at which condensation takes place.

diffusion. The spreading of one kind of gas molecule among others.

dike. A vertical intrusion of magma that has solidified and become exposed through erosion.

diorites. The family of light-colored igneous rocks composed largely of plagioclase and hornblende but no quartz.

discontinuity. A sudden change in the type of material in the earth.

doldrums. The belts of rising air near the equator, with only weak surface breezes.

dome mountains. The mountains formed when magma caused the layered material above it to bulge upward.

Doppler effect. The relative effect of a moving sound or light source.

drumlin. An elliptically shaped hill, steep at the northern end, gently sloped at the other end, and composed largely of clay.

echo sounding. The method of determining the depth of water by sending out a high-pitched sound and timing the return of the echo.

ejecta. The great variety of particles thrown out by a volcano.

elasticity. The ability of a material to return to its original shape after a stress has been applied and removed.

emergent coastline. A coast that has emerged from the water; it is usually gently sloping.

energy. The ability to do work.

English system. The measuring system based on the foot, the pound, and the quart.

epicenter. The point on the earth's surface directly above the underground origin (focus) of an earthquake.

equinox. Two days of the year (beginning of spring and fall) when the sun is at zenith at noon over the equator and every place on earth has 12 hours of daylight and 12 of darkness.

erratic. Huge boulders dropped by a glacier as it melts.

erosion. The wearing away of soil particles.

escarpments. Cliffs found along fracture zones or outlining a plateau.

esker. A winding mound of glacial debris, formed when a subglacial stream eroded its bed into the ice.

extrusion. The molten material within the earth that has risen to the surface of the earth.

facets. The worn, flattened sides of stones, caused by glaciers or by desert winds.

Fahrenheit. The temperature scale using 212 degrees for boiling and 32 degrees for freezing of water.

fall line. A place inland from the sea that was once coastline.

fault. The result of the movement of rock along either side of a crack in the surface of the earth.

fetch. The distance over open ocean that the wind blows.

firn. Partially compacted granular snow.

fission. The disintegration of a piece of matter into energy.

fjord. A long, narrow, steep-walled bay where a glacial valley was eroded below sea level.

flatiron. A triangular slab of sedimentary rock resting against crystalline rock.

fluvioglacial outwash. The material of glacial origin carried away from the melting ice by streams.

focus. The underground point of origin of an earthquake.

foliated rocks. Metamorphic rocks that can be split into layers.

fossils. Plant and animal remains, impressions, or traces of past geologic eras.

fracture. A break in the crust of the earth.

frequency. The number of waves passing a given point in one second.

fringing reef. The coral growing out from the

shore of an island.
front. The border between two different air masses.
fusion. The combining of nuclei of atoms, with some of their mass being converted to energy.
galaxy. A huge cluster of stars.
geologic column. An orderly time sequence of rocks, from the oldest on the bottom to the youngest at top.
geology. The study of the solid part of the earth.
geophysicist. One who studies the physics of the earth, especially earthquake waves, gravity, etc.
geosyncline. A portion of the earth's crust that has been warped downward over a long period of time.
glacial till. A jumbled mass of unsorted debris found in regions once covered by ice sheets.
glacial trough. A U-shaped glacial valley.
glacier. An extended mass of compressed snow and ice that builds up from year to year.
graben. The valley produced when a block of the earth's crust sinks.
granite. A family of rocks that contain quartz and feldspar.
gravity. The natural attraction between the centers of any two pieces of matter in the universe; e.g., objects on the earth and the center of the earth.
groundwater. The water located beneath the earth's surface.
gumbotil. The sticky, clayey soil produced by the weathering of glacial till.
guyots. Flat-topped seamounts.
gyre. A large, slowly rotating area of the ocean.
halite. The mineral name for table salt.
hanging valley. A valley formed by a tributary glacier that ended high on the side of a valley formed by a main glacier.
headlands. High ridges flanking drowned river valleys.
heat. The total motion of the atomic particles of an object.
hogback. The ridge of upturned sedimentary rock that faces a dome mountain.
hook. A sand formation formed into a curve by longshore currents.
horse latitudes. The regions of sinking air about 30 degrees from the equator.
horst. An uplifted section of the earth's crust where a narrow section of rock is involved.
hurricane. A large mass of air whirling at extremely high velocity around a low-pressure area originating in ocean areas.
hydrologic cycle. The recurrent pattern of evaporation, condensation, and the use of water on the earth's surface.
hydrophone. A device that receives echoes from the transducer of a fathometer.
hypothesis. An untested idea in science.
igneous rocks. Rocks that are formed from magma.
inclination of the earth. The tilt of the earth's axis of rotation to the plane of the earth's orbit around the sun.
index fossils. Fossils that are usually found in sedimentary rocks of a particular time period.
insolation. Incoming solar radiation.
interface. The area in which two different kinds of earth material meet.
international date line. The 180th meridian.
International System of Units. The metric system of measure, based on the meter, the gram, and the liter; used by all scientists.
intrusion. The molten material within the earth that has filled spaces between or across layers of sedimentary rocks.
isobars. The lines on a weather map connecting areas of equal pressure.
isostasy. The process of long-range, slow adjustment of the crust of the earth to changing pressures.
isotopes. Atoms of the same element that have nuclei of two or more different masses.
joint. A crack in surface rock.
kame. A mound of glacial debris piled up under a hole that formed in the ice near the melting end of a glacier.
karst regions. The regions where the dissolving of limestone by groundwater has shaped the landscape.
kettle holes. The depressions left when large blocks of ice once buried in glacial debris melted.
kinetic energy. Energy of motion.
knob- and-kettle moraine. A pitted moraine in which many kettles were formed.
laccolith. A mass of magma that has intruded between sedimentary strata and then solidified.
lagoon. A quiet body of water between barrier bar and coast, or within the reef of an atoll.
laminar flow. The smooth, straight-line flow of a fluid.
langley. A gram calorie of energy per square centimeter.
latent heat of condensation. The heat energy given off when a vapor becomes a liquid; for the same amount of matter, this is the same as the latent heat of vaporization.
latent heat of vaporization. The heat energy required to change matter from a liquid to a gaseous state.
latitude. The angular distance north and south of the equator.
lava. The molten material from within the earth that reaches the surface by volcanic action.
law of conservation. The sum of matter and energy in the universe cannot be changed, but matter and energy can be changed from one to the other.

levee. A ridge on the bank of a river, built up from deposition or man-made to prevent overflow.

loess. The wind-blown soil that was often originally fluvioglacial outwash.

longitude. Location measured in degrees east and west of Greenwich, England, the location of the prime meridian.

longitudinal dunes. Dunes lying parallel to the wind direction.

longshore current. A current flowing along the shore.

loran. The abbreviation for Long Range Navigation; a radio navigational aid.

magma. The molten rock beneath the earth's surface.

marine terrace. A wave-cut bench or old beach found below present sea level that is believed to have been the level of the ocean during the Ice Ages.

mass. The measure of the quantity of matter in a body.

meanders. Wide curves found in well-developed streams.

mesosphere. The region of the atmosphere between 50 and 80 kilometers above sea level.

metamorphic rocks. Igneous or sedimentary rocks that have been changed by heat, pressure, bending, chemical action, or a combination of these.

meteors. Masses of stone and iron-nickel from space that collide with our atmosphere.

meteorite. A meteor that reaches the surface of the earth without burning up.

meteorology. The study of the earth's atmosphere.

Mid-Atlantic Rift. The deep valley separating the two parallel ridges of the Mid-Atlantic Ridge.

mid-ocean ridge. A series of mountain ranges found in the ocean basins.

millibar. The metric unit of measurement of force per unit area used for atmospheric pressure. 1013.2 millibars equals 29.92 inches of mercury. A bar is a force of one million dynes per square centimeter of surface.

mineral. A substance that is a unique combination of chemical elements arranged in a specific pattern.

moho. Mohorovicic discontinuity; the contact between the crust of the earth and the mantle.

mold. The kind of fossil resulting from the decay of hard parts after the organism has been buried by sediments.

monadnock. An isolated area of rock that remains sticking up out of a peneplain.

moraines. Piles of loose material dropped by a glacier; usually classified according to position—medial, lateral, terminal.

mT. Maritime tropical air mass.

muskeg. An arctic swamp, which develops because of the permanently frozen undersoil that prevents drainage of the land.

mutation. A change that occurs in the chromosomes and genes of an organism.

nappe. The individual horizontal folds in the crust of the earth.

nebula. A cloud of celestial gases.

névé. Granular ice, formed from melted snow.

nonfoliated rocks. Metamorphic rocks that break into sharp angular pieces.

oasis. A place in the desert where the water table comes close enough to the surface to allow trees to exist.

occluded front. The boundary between a cold and a warm air mass formed in such a way as to lift the warm air from the surface of the earth.

ocean basins. The deep parts of the ocean from which the continents rise.

oceanography. The study of the oceans.

oxbow lake. A lake formed when a meander is completely cut off from the main stream.

ozone. O_3; formed in the stratosphere.

pahoehoe. Ropy lava.

paleontologist. One who studies fossils.

parasite cones. Small volcanic cones that build up on the sides of main volcanoes.

parsec. 3.08×10^{13} kilometers; a measure used by astronomers for celestial distances.

peneplain. A region eroded almost level.

peneplanation. The process of eroding an area almost to a plain.

permafrost. A perpetually frozen layer of undersoil.

petrified. Changed to stone by the replacement of plant or animal material with minerals.

petrology. The study of rocks and their structure.

photons. The tiny particles of energy that compose light.

planet. A celestial body that does not produce its own light and that orbits around a star.

playa. The dry bed of temporary desert ponds or lakes.

polar molecule. A molecule that has charges on opposite sides.

potential energy. Stored energy.

porphyry. An igneous rock with crystals of varying sizes due to irregular cooling.

pressure gradient. The difference in pressure between two points, divided by the distance between them.

pressure waves. Waves that travel with a forward-and-backward progressive motion.

prevailing westerlies. Winds, poleward of the horse latitudes, that have a general pattern of moving diagonally toward the Poles and eastward.

principle of uniformitarianism. The use of the present to explain the past.

protists. Single-celled plants and animals.
quasars. Sources of celestial radio "noise" later found to be dim, starlike objects.
radiant energy. Energy spreading out in all directions from its source.
radioactivity. The process whereby some of the matter within an atom is converted to energy as the atomic nucleus decays.
radioactive isotope. An isotope of an element that loses particles and energy.
refraction. The bending of a wave.
rejuvenation. The upward movement of land.
relative humidity. The ratio between absolute humidity and humidity capacity at a given temperature.
retrograde motion. The apparent change in direction of a planet's motion when viewed from another planet.
revolution. The movement of the planets around the sun.
rhyolite. An igneous rock containing the same minerals as granite but fine-textured because of rapid cooling at the surface of the earth.
rip current. A strong current flowing through a channel between offshore sandbars.
rock. A substance with more or less uniform mineral composition found in large quantities in nature.
rock flour. The finely ground-up rock produced by a glacier.
rock glacier. A pile of talus large enough to extend far out into, and some distance down, a valley.
rotation. The movement of a body on its axis.
salinity. The weight of dissolved salts in 1,000 grams of water.
sand. Particles of rock between 0.06 and 2.00 millimeters in size.
scoria. Small, irregularly shaped masses of ejecta; also called cinders.
sea caves. Caves formed by waves that pound against a rocky coast and loosen the rocks.
seamounts. Isolated underwater mountain peaks.
sea stacks. Pillars of more resistant rock left as wave action erodes a rocky coastline.
sediment. The mineral particles carried by a stream.
sedimentary rocks. Rocks made of sediments that have been cemented together.
seif. An accumulation of sand dunes.
seismograph. An instrument that records elastic waves moving through the earth's crust caused by earthquakes, etc.
serac. A huge block of ice caused by the intersection of crevasses.
shadow zone. The zone from about 102 degrees to about 143 degrees from the epicenter of an earthquake, where seismographs record few if any waves.
shear wave. A wave that vibrates at right angles to the direction of wave travel.
shield cone. A volcano composed of solidified lava; this type composes the Hawaiian Islands.
sial. Continental crystalline rocks rich in silica and aluminum.
sima. Ocean-floor crystalline rocks rich in silica and magnesium.
sinkholes. Deep pits formed when rock is dissolved along joints in a limestone region.
slipoff. The side of a meandering stream on which debris is being deposited.
soil. Finely divided rock particles mixed with organic material; found on the surface of the earth.
solar prominences. Great spurts of glowing gases that periodically extend outward from the chromosphere.
solstice. Two days, June 21 and December 21, when the sun is at zenith 23½ degrees north or south of the equator.
specific heat. The number of calories of heat energy that must be added to one gram of a substance to raise its temperature one degree Celsius.
spectrum. The range of wavelengths of visible light.
spit. A sandbar built up above sea level and attached to shore at one end.
stalactites. Travertine deposits that hang like icicles from the ceiling of a cave.
stalagmites. Travertine deposits that build up from the floor of a cave.
standard time zones. Zones 15 degrees in width, with the time being that of the meridian near the center.
star. A celestial body, with a "fixed position," giving off its own light.
stationary front. The boundary between a cold and a warm air mass where there is little movement.
stone. A piece of a rock.
stratosphere. The layer of the atmosphere above the troposphere extending upward to about 38 miles above sea level.
striae. The scratches on rock caused by the abrasion of a glacier.
submarine canyons. Steep valleys that cut across continental shelves.
submergent coast. A coast that has been covered with water; usually rocky.
summer solstice. June 21, when the sun's rays are directly overhead at 23½° north latitude.
swells. Waves that are no longer being built up by the wind.
syncline. A downward fold of the earth's crust.
talus. The jumbled debris found at the base of a slope.
tarn. A small lake left in a glacial rock basin.
tectonic earthquake. The vibrations produced where masses of rock rub against one another.

tektites. Small glassy objects found in nature but of unknown origin.

temperature. The average motion of the atomic particles of an object.

temperature inversion. The temperature condition when a mass of cold air is trapped beneath a mass of warm air.

thermal gradient. The rate of temperature change.

thermosphere. The layer of the atmosphere above the mesophere.

thrust plane. An area of contact between alpine-folded sedimentary rock and crystalline bedrock, or the plane of a fault.

tidal bore. A tide wave that moves far up into a bay.

tide wave. A wave caused by the gravitational pull of the sun and the moon on the ocean waters.

tombolo. An offshore island that becomes attached to shore as wave action piles sediments in the shallow sea between the shore and the island.

trade winds. Winds equatorward of the horse latitudes that blow diagonally toward the equator and westward.

transducer. A device attached to the bottom of a ship or towed behind that make a high pitched noise.

transverse dunes. Dunes lying at right angles to the direction of the wind.

travertine. A form of the mineral calcite associated with springs and caves in limestone areas.

troposphere. The layer of our atmosphere closest to the earth.

tsunami. A sea wave caused by earth movements.

tundra. The regions in front of the ice caps that have sparse vegetation.

turbulent flow. An irregular flow in a fluid.

typhoon. A storm similiar to a hurricane, but found along the western margin of the Pacific.

unconformity. An interruption in the layering of sediments.

upwelling. An upward movement of cool water along a coast to replace warm surface water blown away by the wind.

vernal equinox. March 21, when the sun is directly over the equator and night and day are of equal length.

volcanic bombs. Chunks of lava hurled through the air from a volcano and shaped by the movement.

volcano. A vent in the crust of the earth through which gases and particles are expelled from beneath the surface.

warm front. A mass of warm air advancing into a territory covered by cold air.

water gaps. Streams that maintain their beds as land is uplifted, forming gaps through the mountains.

watershed. The land from which a stream system collects water.

water table. The underground level beneath which the soil is always saturated with water.

wave. A disturbance or vibration that moves progressively through a medium.

wave height. The vertical distance from the bottom of the trough to the top of the crest.

wavelength. The distance from one wave crest to the next.

weathering. The breaking down of solid rock into smaller pieces.

weight. The effect of gravity on a mass.

wind arrow. The mark on a weather map pointing in the direction from which the wind is coming.

wind gap. An abandoned stream valley through the mountains.

wind vane. An instrument used to show the direction of the wind; it points in the direction from which the wind is coming.

winter solstice. December 21, when the sun's rays are directly overhead at 23½ degrees south latitude.

zenith angle. The angle that the sun's rays make with a flat surface, measured from a line perpendicular to that surface.

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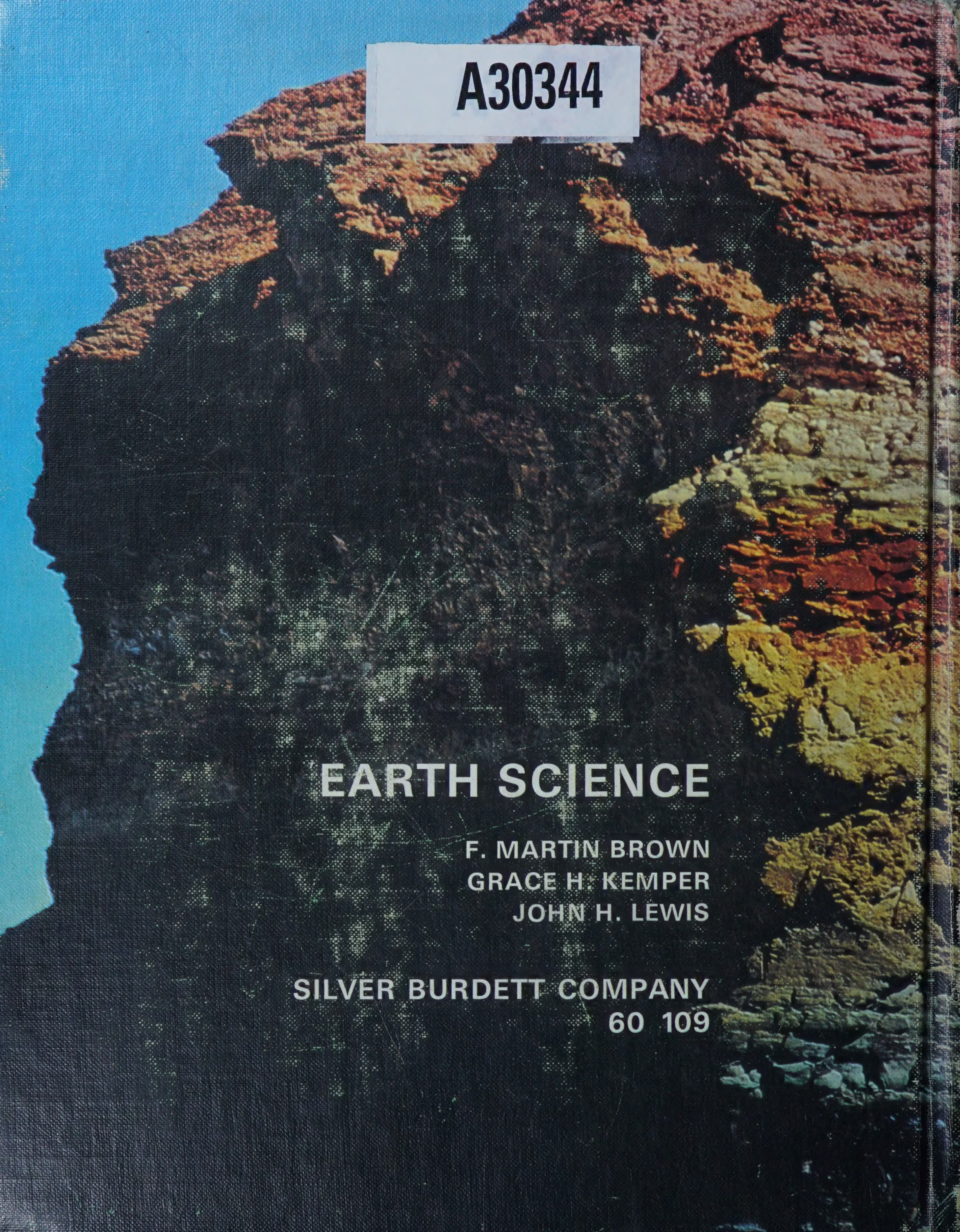

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